DEALING WITH UNCERTAINTY IN SUPPLY CHAIN DESIGN IN THE AUTOMOTIVE INDUSTRY

by

Lia Coelho de Oliveira

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Under the supervision of:
Professor Jorge Manuel Pinho de Sousa
and
Professor João Alberto Vieira Campos Pereira Claro

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Á minha *Mãe Nandita*

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"Valeu a pena? Tudo vale a pena

Se a alma não é pequena.

Quem quer passar além do Bojador

Tem que passar além da dor.

Deus ao mar o perigo e o abismo deu,

Mas foi nele que espelhou o céu."

Fernando Pessoa

A todos o meu Muito Obrigada, sem vocês não teria sido possível!

Abstract

Industrial organizations set their efforts more and more on the control and reduction of costs, not only as a way to fight a growing market competition but also to recover from the problems posed by the current global economic and financial crisis. The automobile is one of the most affected industrial sectors, facing a decrease in the sales of vehicles and an increase of the prices of oil and steel, since the last quarter of 2008. The economy slowdown has contributed to a profound restructuring in this sector, as a reaction to the considerable fluctuations in sales (decrease of the automotive demand) with considerable impacts in all automotive supply chain partners. To go on being competitive, automotive companies need to improve their own networks and the way they relate with the market, to promote innovation (viewed as a critical success factor), and to invest in activities planning and in supply chain opportunities. It is therefore fundamental for companies to be able to systematically evaluate and design their production and distribution systems, as well as their strategies, in order to provide the desired customer service level at the lowest possible cost (Goetschalckx et al. 2002).

In this context, research on supply chains has been strongly fostered by the need to improve systems already in place or to build new, more efficient and effective systems (Hugos 2006). More recent research is related with decisions on the allocation of products to plants, plant sizing (capacity), strategic planning processes, and investment decisions on new facilities or on capacity expansion and supply chain design.

Supply chain management is a fundamental discipline in the automotive industry. In our interaction with the industry, we identified several uncertainty factors relevant for the design and operation of automotive supply chain networks. A literature review on this topic revealed a research gap: most of the few models found in the literature for this industrial sector are of a deterministic nature, thus neglecting uncertainty. The stochastic models only consider the production sector and the impact of demand uncertainty. In this work we extended those models to explicitly consider uncertainties across the entire supply chain, and to develop a stochastic approach for the design of global automotive supply chain networks that supports strategic/tactical decision-making. Other characteristics also considered in these models are multiple periods (to model impacts of changes in the future), multiple objective functions (to tackle the trade-offs between costs and customer service level) and international parameters (as legislation).

The main goal of our research was to develop a model for the automotive supply chain, capable of supporting and improving decision-making, of dealing with (typical and extreme) uncertainties and of taking into account risk and the chain vulnerabilities.

The developed model is able to support decision-making for a yearly operations strategy planning, helping us understand how the supply chain network might evolve in a long-term horizon, in order to optimize the profitability of operations. For this purpose,

the model is able to: define different scenarios for the future evolution of supply, demand, transportation and other critical elements of the supply chain network; analyze relevant new investment alternatives (opening or closing factories, increasing or decreasing capacity, opening or closing warehouses); simulate and optimize investment decisions in time.

Our work had also a clear concern of matching scientific research with results of relevance for the industry. For that purpose we have established a partnership with an industrial company in the sector, which has provided data and guidelines, and has helped us to identify the main requirements of the model, as well as its structure. Comparing and combining the industry and literature inputs we have defined the main lines of our research and the components of our models.

Resumo

As organizações industriais têm vindo, cada vez mais, a direccionar os seus esforços para o controlo e a redução dos custos, não só como forma de combater a crescente concorrência, mas também como um processo de recuperar dos problemas originados pela actual crise económico-financeira global. O sector automóvel é um dos sectores industriais mais afectados, enfrentando uma queda nas vendas de veículos e um aumento dos preços do petróleo e do aço, desde o último trimestre de 2008. A desaceleração da economia tem contribuído para uma profunda reestruturação no sector, como reacção às flutuações consideráveis na procura (diminuição acentuada do volume de vendas) e levando, consequentemente, a uma pressão cada vez maior junto de todos os parceiros da cadeia de abastecimento. Para continuarem a ser competitivas as empresas do sector automóvel precisam de focar os seus esforços no melhoramento das suas próprias redes e na forma como eles se relacionam com o mercado, promover a inovação (vista como um factor crítico de sucesso), e investir em actividades de planeamento e oportunidades da cadeia de abastecimento. Deste modo, torna-se crucial que as empresas sejam capazes de desenvolver os seus sistemas de produção e distribuição, bem como as suas estratégias, para serem capazes de oferecer ao cliente o nível de serviço desejado com o menor custo possível (Goetschalckx et al., 2002).

Neste contexto, a investigação sobre as cadeias de abastecimento tem sido fortemente estimulada pela necessidade de melhorar os sistemas já existentes ou de construir novos sistemas, mais eficientes e eficazes (Hugos, 2006). Em trabalhos de investigação mais recentes, o ênfase tem sido posto nas decisões sobre a alocação de produtos a fábricas, o dimensionamento de fábricas (capacidade de produção e armazenamento), o aperfeiçoamento de processos de planeamento estratégico, ou ainda sobre a tomada de decisão de investimento em novas instalações, ou na expansão de capacidade, em linha com o "redesenho" da cadeia de abastecimento.

A Gestão da Cadeia de Abastecimento ("Supply Chain Management") é uma área fundamental para a indústria automóvel. Na revisão da literatura sobre o tema foi identificada uma importante lacuna na investigação desenvolvida até à data: dos poucos modelos encontrados para o sector automóvel, a grande maioria são de natureza determinística, negligenciando, assim, a incerteza. Os modelos estocásticos que consideram o sector industrial em estudo centram-se na área produtiva e no impacto que a incerteza na procura poderá ter. Neste trabalho estendemos esses modelos, com o objectivo de considerar explicitamente as incertezas em toda a cadeia de abastecimento, não nos focando apenas numa das suas partes. Assim, desenvolvemos uma abordagem estocástica para o projecto de redes de cadeia de abastecimento do sector globalmente considerado, que permite apoiar a tomada de decisão, quer a nível estratégico, quer a nível táctico. Outras características também consideradas nestes modelos são: múltiplos períodos (para modelar os impactos das mudanças no futuro), múltiplas funções objectivo

(para tratar os trade-offs entre custos e nível de serviço ao cliente) e parâmetros cobrindo os aspectos internacionais do problema (por exemplo legislação).

Em linha com estas preocupações, o principal objectivo de nossa investigação foi desenvolver um modelo para a cadeia automóvel, capaz de apoiar a tomada de decisões, de lidar com incertezas (típicas e extremas) tendo em conta os riscos e as vulnerabilidades a que as cadeias de abastecimento estão sujeitas.

O modelo desenvolvido neste trabalho pode ser de grande utilidade para apoiar a tomada de decisão no planeamento estratégico, ajudando-nos a entender como a cadeia de abastecimento pode evoluir num horizonte temporal de longo prazo, a fim de optimizar a rentabilidade das operações. Para este efeito, o modelo é capaz de: definir diferentes cenários para a evolução futura da procura, oferta, transporte e outros elementos críticos da rede; analisar novas alternativas de investimento relevantes (abrindo ou fechando fábricas, aumentando ou diminuindo a capacidade, abrindo ou fechando armazéns), simular e optimizar as decisões de investimento ao longo do tempo.

O nosso trabalho teve também uma clara preocupação de combinar investigação científica com resultados com relevância para o sector. Para esse efeito, foi estabelecida uma parceria com uma empresa industrial do sector, que forneceu dados e orientações, e nos ajudou a identificar as principais necessidades do modelo, bem como a sua estrutura.

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1. Introduction

In this first chapter we present the motivation for this doctoral project, the issues addressed in the work and its main goals, along with the adopted methodological approach. A reference is made to the industrial case study considered in the work. The problem statement and research questions are also presented, introducing the relevance and contributions of our research.

1.1. Motivation

Industrial organizations set their efforts more and more on the control and reduction of costs, not only as a way to address intensified competition, but also to support their recovery from the challenges posed by the current global economic and financial crisis. In recent years, companies have intensified their attention to the field of supply chain design, seeking to become more competitive in increasingly globalized environments. The global economic and financial crisis further reinforced its importance to industrial organizations.

The financial crisis of 2008 was viewed by many economists as the worst financial crisis since the Great Depression of the 1930s. Starting with the subprime mortgage crisis, we saw the bursting of the United States housing bubble. As housing prices declined, major global financial institutions that had borrowed and invested heavily in subprime lending reported significant losses. Defaults and losses on other loan types also increased significantly as the crisis expanded from the housing market to other parts of the economy. The total collapse of large financial institutions, the bailout of banks by national governments and downturns in stock markets around the world were unavoidable. The crisis rapidly developed and spread with a global economic impact, resulting in a number of European bank failures, declines in various stock indexes, and large reductions in the market value of equities and commodities[1] (Baily et al., 2009; Gore, 2010; Wessel, 2010).

This global financial crisis caused a deep contraction of economies. Around the world a strong decline in industrial production took place, with record figures in the unemployment rate, political instability related to the economic crisis (strikes, early elections), increased emigration rates, a significant increase in oil prices (with a strong recession effect) and a generalized deterioration in living standards[2] (Evans-Pritchard, 2007; Norris, 2008; Sicilia,2012; ; Shilton, 2008).

The automotive was one of the most affected industrial sectors, facing a decrease in the sales of vehicles and an increase of the prices of oil and steel, the key raw materials, since the last quarter of 2008. In parallel, there is a growing concern with the reduction of

[1] Based on: "Two top economists agree 2009 worst financial crisis since great depression; risks increase if right steps are not taken." February 29, 2009. Publish by *Reuters*.
[2] "Statician says U.S. joblessness near Depression highs". Reuters. 2009-03-09. Retrieved 2010-01-21

CO_2 emissions. The economy slowdown has contributed to a profound restructuring in this sector, as a way to react to the considerable fluctuations in sales (decrease of the automotive demand) and consequently to a higher pressure in all automotive supply chain partners (Weller, 2008; Rippert,2008; Shilton, 2008). To go on being competitive, automotive companies need to improve their own networks and the way they relate with the market, to promote innovation (viewed as a critical success factor), and to invest in activity planning and in supply chain opportunities. It is therefore fundamental for companies to be able to systematically evaluate and redesign the production and distribution systems, as well as their strategies, to provide the desired customer service level at the lowest possible cost (Goetschalckx et al. 2002).

In this context, research on supply chains has been strongly fostered by the need to improve systems already in place or to build something new (Hugos, 2006). More recent research is related with decisions on the allocation of products to plants, plant sizing (capacity), strategic planning processes, and investment decisions on new facilities or on capacity expansion and supply chain design.

Contributing to a better understanding of these issues is the most general motivation for this doctoral project, taking also into account a strong motivation to develop research in an industrial environment, and guaranteeing a deep interaction between scientific and industrial activities.

Accordingly, the project deals with the need to:

- develop a model to support strategic and tactical decision-making;
- integrate risk management concerns, improving the reaction to uncertainties, dynamics and accidents (vulnerabilities);
- contribute to increasing the efficiency of supply chains.

A supply chain network in the automotive industry (Simoldes Group, in Europe) was used as a case study. With this company we have done a careful discussion and definition of the project scope and goals, to be sure there was a clear alignment between our research objectives and their expectations. In our specific case, we have identified Simoldes Group as the right industrial partner for our research purposes. They work directly with the automotive industry as suppliers, with a huge diversity of supply chain members from several countries. Their major customers are OEMs and they recognize that some of the major problems they have to face in their own daily routine are problems approached by our research work.

Firstly, they identify some difficulties related with decision-making at strategic and tactical levels. Regarding the strategic level, some strategic decisions can be episodic. For example, a customer (OEM) is opening a new factory and wants us to build a collocated plant to supply that new factory. We need to understand how supplying this new customer site can best be integrated, in time, with his supply network, and how this interacts or conflicts with the conditions of our previous contractual agreements. The second problem described concerns decision support for annual operations strategic planning, helping to understand how the supply chain network might evolve in a long-term horizon, to optimize the profitability of operations.

The project has been developed with the concern of following two parallel and complementary "lines" (see Figure 1). The first of these lines is directly related to the doctoral project, with contributions of a scientific nature, knowledge production, and innovative results supported by a sound literature review and state-of-the-art. On the other hand we have searched and characterized a case study capable of representing well the structure of companies in the automotive sector, as a way to produce more general guidelines and results. Data availability was also a major concern in this choice. The clear definition of these two work directions, along with their alignment was key to guaranteeing the success of the research project (the PhD thesis) and matching the expectations of Simoldes in terms of practical results.

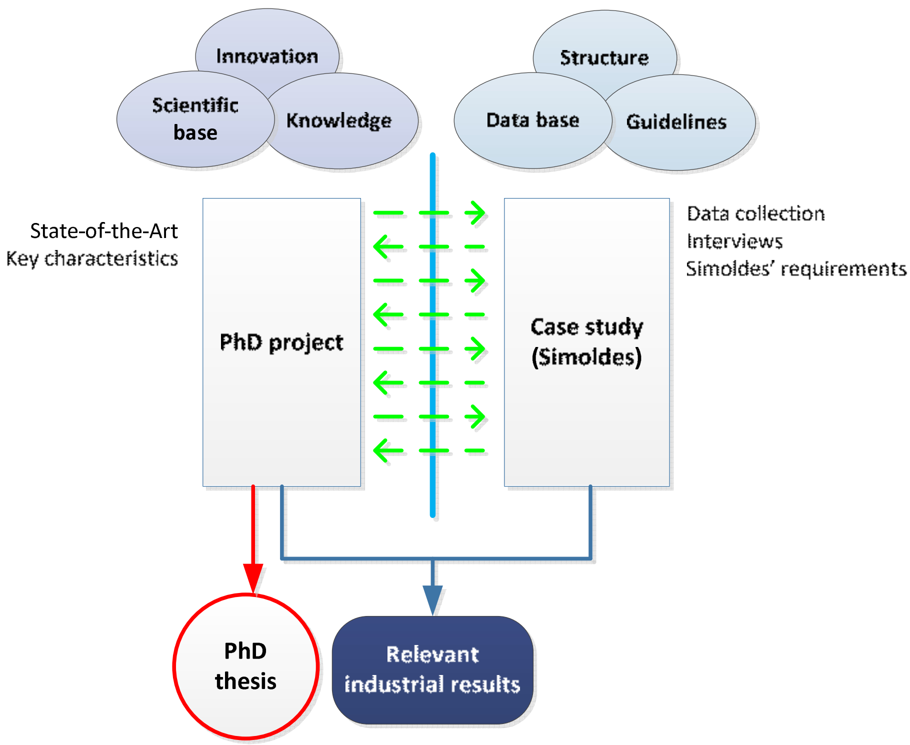


Figure 1: General project organization

1.2. Problem statement and research question

Supply chain management is recognized as a crucial discipline to companies, helping in one of the most frequent and common concerns to all kinds of companies, reduction of costs. This concern has been intensifying at a time when enormous resources are used to recover from the disruption motivate by the strong financial crisis. It is natural that industrial organizations set their efforts more and more on the control and reduction of costs. The automotive industry is recognized as one of the most affected industrial sectors, facing a decrease in the sales of vehicles and an increase of the prices of oil and steel, since the last quarter of 2008. To pursue competitiveness, automotive companies need to improve their own networks and the way they relate with the market, to promote innovation, and to invest in activity planning and in supply chain opportunities. Supply chain management already played a prominent role in the automotive industry, but after 2008 becomes further vital. Supply chain design should be strongly influenced by the dynamics of markets that are associated to high levels of uncertainty (risk management), an aspect that has been neglected in the literature. There are few models addressing automotive supply chain networks, and most of these either are deterministic, or just consider uncertainty in production (and not in the entire supply chain) and demand (Bihlmaier et al., 2009), thus neglecting uncertainty factors that have become more relevant in modern supply chains.

In line with these considerations, we have defined for this doctoral project the following general research question.

> ***Research Question:*** *How can we improve strategic and tactical decision-making process, considering dynamics and uncertainty in automotive supply chains, through the use of optimization models?*

The relations between the main concepts and goals considered in the reach question are presented in Figure 2.

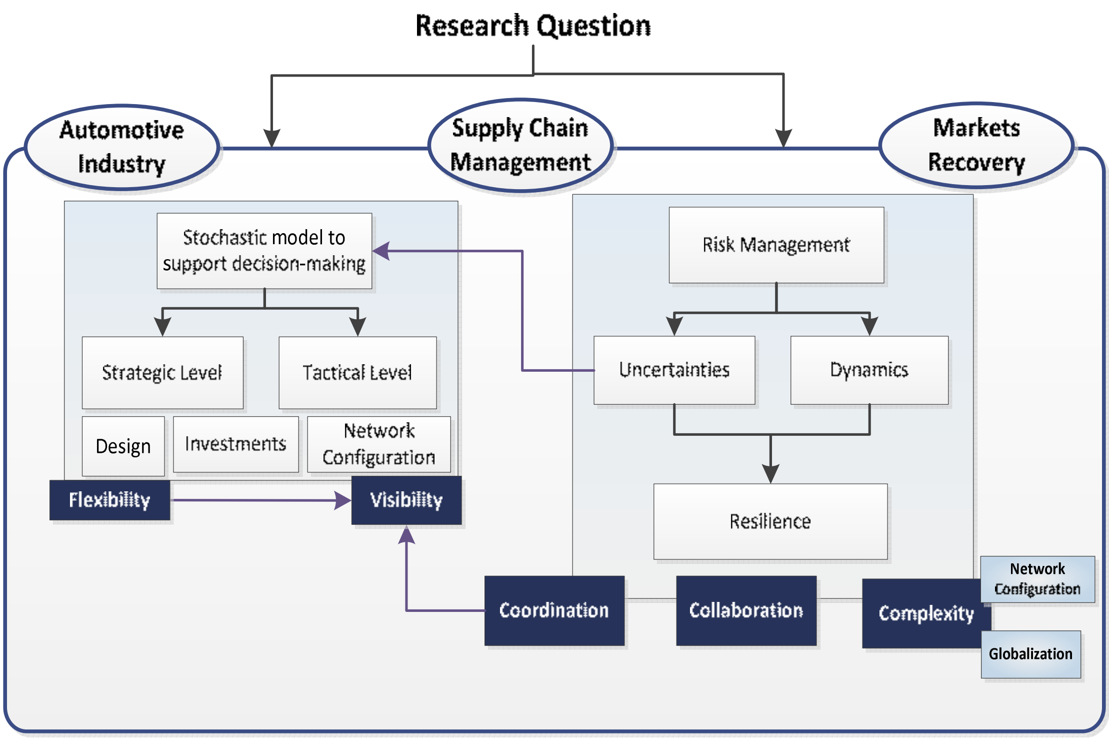


Figure 2: Research question

The main objective of our work is to contribute to fill this gap by extending previous models to explicitly consider uncertainty factors, such as interest rates or extreme events (e.g., sudden disruptions of the network). The developed stochastic optimization model takes into account the specific features of global modern automotive supply chains and aims at supporting strategic and tactical decision-making. Our work is also intended to tackle two types of uncertainties – extreme and typical (or normal) uncertainties. So, the main goal of our research it to develop a model for the automotive supply chain, to help improve the decision-making process, dealing with (typical and extreme) uncertainties and taking into account risk and supply chain vulnerabilities.

Extreme uncertainties have been studied with a qualitative approach, relating the characteristics of the system with resilience. But we have also developed an extension to our base model that considers the probability of occurrence of this type of events (e.g., a hurricane) in a specific geographic zone. Typical uncertainty factors were studied using quantitative data. We have tried to establish the links between these uncertainties, related to the possible levels of cooperation, collaboration and visibility, with the capacity to be flexible.

Hence, our research project can be somehow summarized in the scheme of Figure 3.

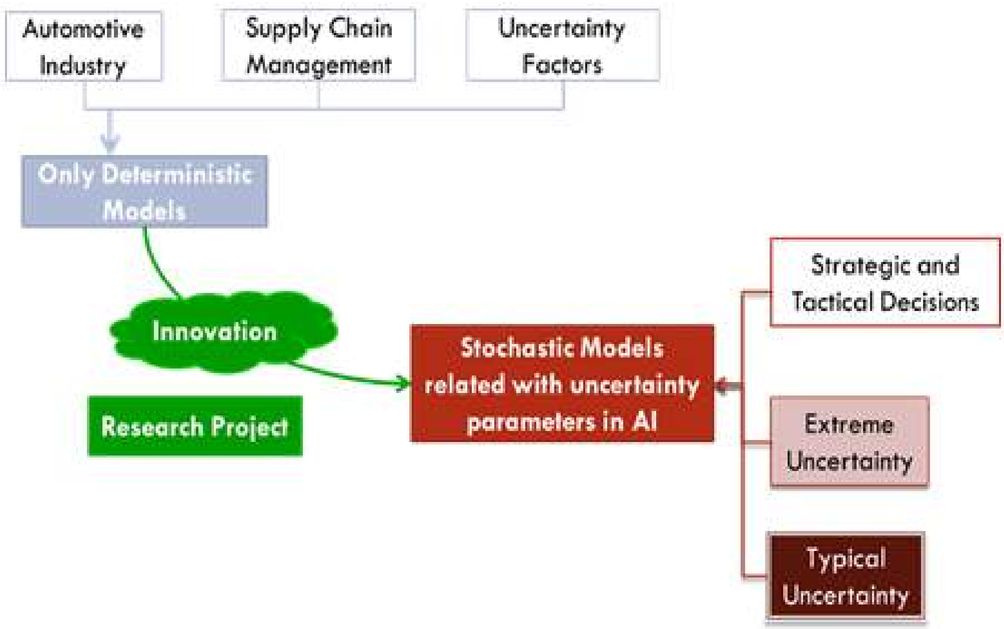


Figure 3: Scope of the research project (AI: Automotive Industry)

We expect to contribute to improving the efficiency of supply chain management, taking uncertainty into account during the decision-making process. Most of the few models found in the literature for this industrial sector are of a deterministic nature, thus neglecting uncertainty. The stochastic models only consider the production sector and the impact of demand uncertainty. In this work we aim at extending those models to explicitly consider uncertainties across entire supply chain, and to develop a stochastic approach to global automotive supply chain networks, that supports strategic/tactical decision-making. Other characteristics should also be considered in these models, namely: multiple periods (to model impacts of changes in the future), multiple objective functions (to tackle the trade-offs between costs and customer service level), international parameters (as legislation), etc. The innovation proposed in our work consists in developing a stochastic model that tackles a set of uncertainty parameters (for extreme and typical uncertainties) in the automotive industry, supporting decision making at tactical and strategic levels related with entire supply chain.

1.3.Structure of the research project

This research project was structured around five main modules: idea conception; literature review, development of the base model (during an internship period, at Simoldes); generalization and synthesis of results.

The “idea conception” consisted in refining the initial ideas using brainstorming. After this step, the investigation question was formulated and the project research goals were identified.

The development of the “State-of-the-Art” has included five main steps: a critical review of the literature (literature sources: primary; secondary and tertiary); problem structuring (specifying the meaning of concepts and variables to be studied); requirement analysis (performed with the industrial partners); and the definition of how we will measure the identified variables. During this period we started the internship with the industrial partner, and spent some months at the Massachusetts Institute of Technology (MIT).

The next step had the objective of choosing the research approach and strategy. At this stage we also needed to guarantee the access to corporate information and address some ethical issues (what information can be published?). Consequently we defined the plan and the methods for data collection (a mix of interviews and observation), and subsequently collected the data. After the data had been collected, it was necessary to give this data the adequate form for manipulation and analysis. This data was used in our qualitative and quantitative analyses.

Finally we defined the model scope and details, starting a new step focused on the development of mathematical models. This phase included the design, evaluation and implementation of modeling procedures to handle the problems identified in the case study characterized for the pilot. As referred, these procedures included the development of a stochastic optimization model dealing with uncertainty in the automotive industry strategic and tactical decision making, as well as, the vulnerabilities of modern supply chain and risk management.

The last step consisted in the generalization and reporting of results, with a special focus on the innovative contributions and their practical impacts on industry. An assessment of those results and main contributions was performed.

Figure 4 summarizes the activities of the doctoral project described in this dissertation.

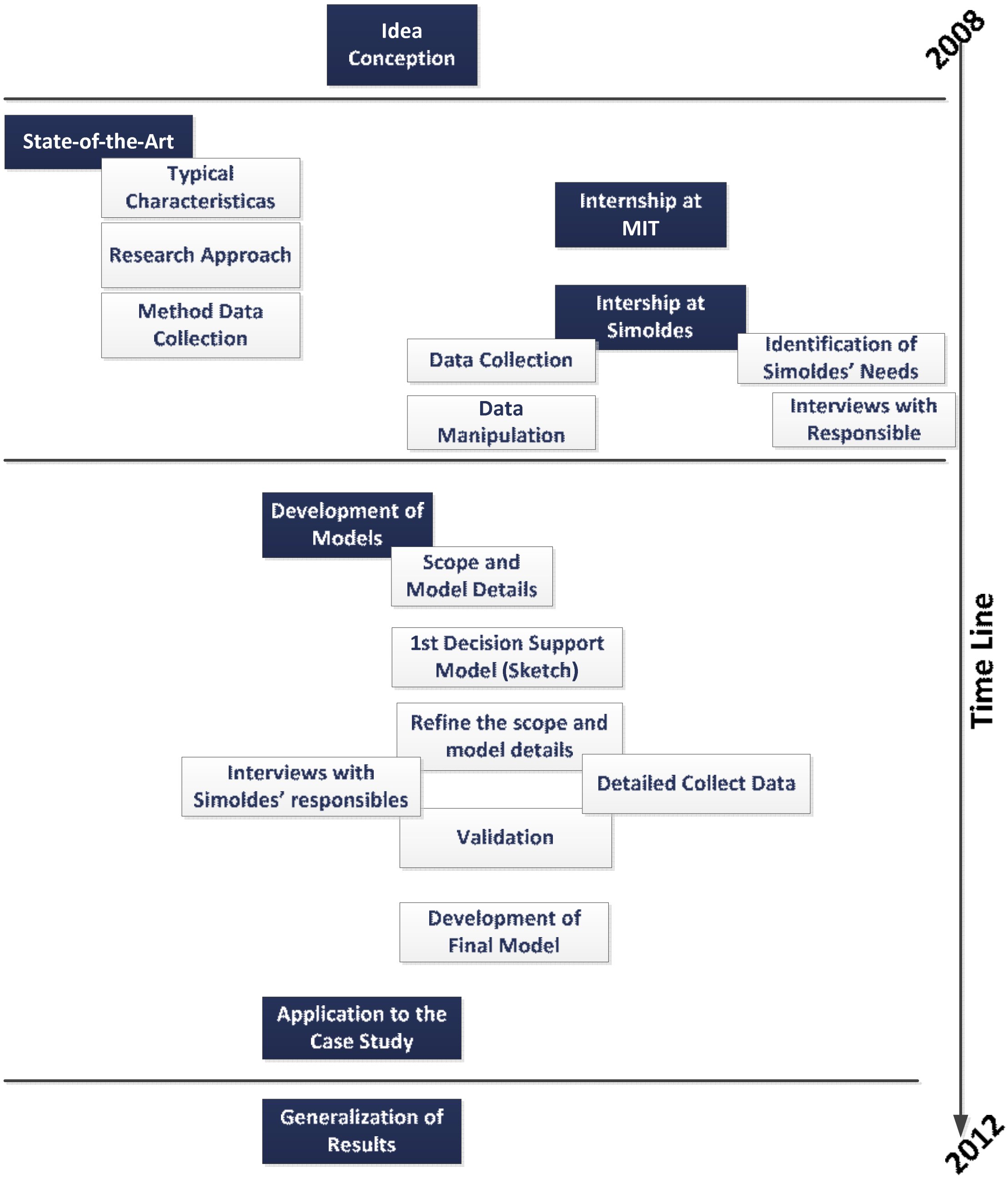


Figure 4: Research project

1.4. Thesis outline

This dissertation is organized as follows. In Chapters 2 and 3, we review the main relevant concepts, the research work developed in this scientific field, particularly addressing the automotive industry, the use of network design under uncertainty, and stochastic models in the domain. In Chapter 4, we introduce the case study describing the company, the data collected, the work developed during the internship at the company, and we conclude with a problem generalization. Chapter 5 presents the main contribution of this work, a model to deal with uncertainty in supply chain design: a new mathematical formulation is proposed and evaluated. A more embracing model with four different extensions is presented in Chapter 6, with the applicability and usefulness of these models being fully discussed. Chapter 7 concludes this thesis with a summary of the main research contributions and implications of our work, along with some suggestions for future research.

2. Context and State-of-the-Art

In this chapter we summarize the main findings of a comprehensive literature review mainly related with supply chains. Several key inter-related concepts and ideas have been identified, helping us to understand processes and also their associated dynamics.

This review has been pursued in order to define the right context for the work, in terms of Supply Chain Management and Networks, viewed as the main domains for this research project. Thereby we describe the connection, definitions and main characteristics related with uncertainty factors, automotive industry, risk management, flexibility, collaboration and types of decisions.

2.1. Context

Industrial organizations are more and more setting their efforts on the control and reduction of costs, not only as a way to fight a growing market competition but also to overcome the problems posed by the current global economic and financial crisis. The automobile is one of the most affected industrial sectors, facing a decrease in the sales of vehicles and an increase of the prices of oil and steel, since the last quarter of 2008. At the same time, there is a growing concern with the reduction of CO_2 emissions. The economy slowdown has contributed to a profound restructuring in this sector, as a way to react to the considerable fluctuations in sales (decrease of the automotive demand) and consequently to a higher pressure in all automotive supply chain partners. To go on being competitive, automotive companies need to improve their own networks and the way they relate with the market, to promote innovation (viewed as a critical success factor), and to invest in activities planning and in supply chain opportunities. It is therefore fundamental for companies to be able to systematically evaluate and design the production and distribution systems, as well as their strategies, to provide the desired customer service level at the lowest possible cost (Goetschalckx et al. 2002).

In this context, research on supply chains has been strongly fostered by the need to improve systems already in place or to build something new (Hugos 2006). More recent research is related with decisions on the allocation of products to plants, plant sizing (capacity), strategic planning processes, and investment decisions on new facilities or on capacity expansion and supply chain design.

Supply chain design involves decisions about the number, location, size and specific capabilities of manufacturing plants and warehouses, as well as the distribution and the sourcing processes (subcontractors and 3PLs) of a company (or a set of collaborating companies) in order to provide goods to customers. It also involves decisions related to the selection of suppliers (Klibi et al. 2010). The global goal is in fact to determine the physical configuration and the supporting infrastructure of a supply network. In the graphic representation of these networks normally the nodes are the facilities that are connected by links/arcs that represent direct transportation flows.

A supply chain network is traditionally characterized by a forward flow of materials and goods (associated to transportation activities) and a backward flow of financial resources and information (a global supply chain network is illustrated in Figure 5).

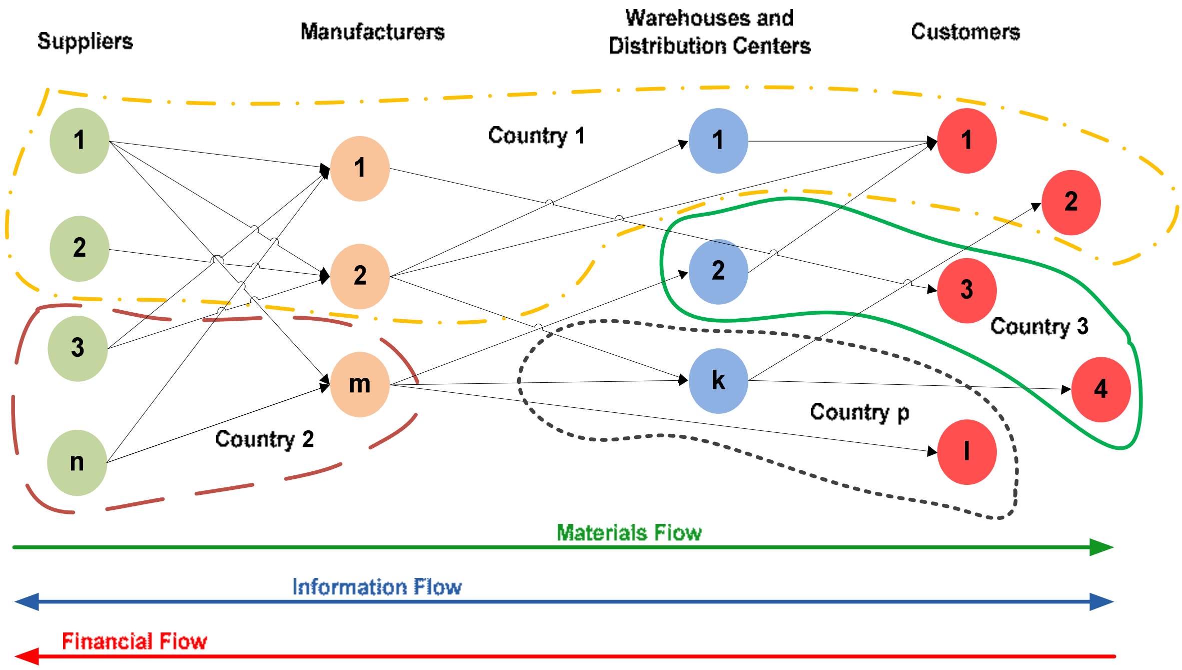


Figure 5: Global supply chain network

Supply Chain Design alone is not enough to answer the requirements of modern supply chains. Thus it is supported by Inventory Positions and Management (the definition of the inventory policy), as well as by Resources Allocation. These are the three main steps in Supply Chain Planning. The goals of this planning process are: to find the right balance among inventory, transportation and manufacturing costs; to match supply and demand under uncertainty by positioning and managing inventory effectively; and to use resources efficiently in a dynamic environment (Simchi-Levi et al. 2003, Blackhurst et al. 2004).

The decisions from Supply Chain Planning can take place at any of the three hierarchical levels: strategic, tactical and operational.

In general, the strategic level involves a time horizon of more than 1 year and decisions about the configuration of the network (production topology; the number, location, and capacity of technology facilities), product selection, product allocation among plants and vendor selection for raw materials. Decisions at this level require a large investment in capital over long periods of time.

The tactical level involves decisions about the aggregate quantities and material flows for purchasing, processing, and distribution of products. It aims at obtaining a best utilization of the available resources. These decisions are focused in medium term time periods, from 1 month to 1 year.

Finally the operational level has a short time horizon (e.g., 1 hour, 1 day or 1 week) and typically it involves decisions related with master production scheduling (e.g., production volume, transportation orders, purchase orders) (Landghem and Vanmaele 2002; Santoso et al. 2005; Alonso-Ayuso et al. 2003; Dogan et al. 1999).

Most of the decisions taken at the different hierarchical levels previously described can be based on models with single or multiple periods, and these models can be deterministic or stochastic (i.e., they can explicitly consider uncertainty parameters).

2.2. Networks

In general terms, industrial organizations can establish two types of external relationships: alliances and/or networks. Street and Cameron (2007) cites Spekman et al. (2000) to define alliance as follows: “alliance is a close, collaborative relationship between two, or more, firms with the intent of accomplishing mutually compatible goals that would be difficult for each to accomplish alone.”

For the network concept there is a variety of definitions depending of the scientific discipline (e.g., microbiology, ecology, technology). In 1995 Rosenfeld defined network as “a group of firms with restricted membership and specific, often contractual business objectives likely to result in mutual gains. Network members choose each other; agree explicitly to co-operate in some way (common goals) and to depend on each other to some extent.” (cited by Cooke, 1998).

Considering the definitions developed in recent years by several authors, and trying to encompass the main contributions from the literature, in this work we view a network as a set of autonomous entities (individuals, companies and other organizations such as government and non-profit agencies) that establish formal and informal linkages, to develop goods or services based on implicit and open-ended contracts, using their combined talents and resources. These relationships allow network members to solve common problems, achieve collective efficiency and conquer new markets beyond their individual reach (Ffowcs-Williams, OECD, 2003; Street et al., 2007). The process of communicating and exchanging information for mutual benefit is normally called networking.

In networks a fundamental activity is the integration and harmonious adjustment of individual work efforts, towards the accomplishment of a larger goal. This is called coordination.

The success of industrial organizations depends a lot on their collaboration with other organizations in the networks that they belong to, influencing the creation and delivery of their goods or services.

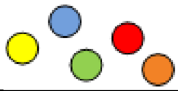
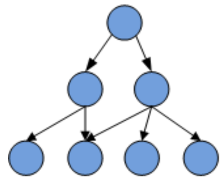
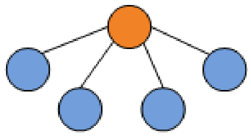
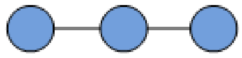
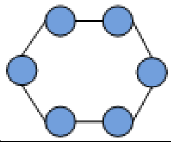
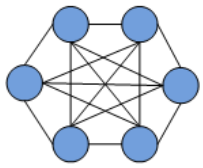
Collaboration occurs when two or more companies exchange information on planning, management, execution, and performance measurement, to achieve a common goal (Anthony, 2000). This term is derived from the Latin *collaborare* meaning “to work together” and it is a fundamental process involving all network entities and leading to the enhancement of the capabilities of each other. Collaboration is based on sharing of resources, responsibilities and information, in real time, with considerable detail and reducing information errors. (Milgate, 2001; Simchi-Levi et al., 2003; Vachon et al., 2002; Kapia, et al., 2007). Collaborative relationships foster information sharing between network members and drive changes in the underlying business processes. The success of industrial organizations depends a lot on their collaboration with other organizations, influencing the creation and delivery of their goods or service.

2.2.1. Network topology and typology

Networks may be very complex and they are based on a series of bilateral relationships that can be hierarchical or non-hierarchical. Hierarchical relationships (in a hierarchical network) are characterized by the existence of one leading partner that controls the network and settles the operational rules. In a non-hierarchical network all partners have the same status, that is to say, no one has a special position or leads the network. Therefore, all decisions affecting the partnership are mutually agreed on. In this network type one partner may take the coordination responsibilities, but has no dominant status over the other partners.

Table 1 presents some representative network topologies (briefly described in text and in a graphic way). The centralized, linear, federated and flat structures are often non-hierarchical networks, although in some of these types, decisions are not determined by all partners (Pathak et al., 2009).

Table 1: Networks Topology

Topology	Description	Graph representation
No Structure	No edges are formed in the graph. Each firm operates independently.	
Hierarchical (Tree)	There is a central partner that is connected to one or more other partners that are one level lower in the hierarchy. These partners are themselves connected with one or more partners that are one level lower in the hierarchy.	
Centralized (Star)	There is a central partner connected with each one of the other network partners. But the others partners are not connected among them.	
Linear (Bus)	All partners are connected together by a single relation (link).	
Federated (Ring)	Each partner is connected to the network in a closed loop or ring.	
Flat (Mesh)	All partners communicate between themselves.	

Network types have been studied in recent years by numerous authors. In this work we have analyzed several different typologies and focused our attention in two specific typologies: Möller et al. (2005), and Valkokari et al. (2007).

The typology developed by Möller et al. (2005) considers the value-system information combined with the goals of the network actors and the structure of the network. They claim that most existing networks can be in one of the following 3 types:

- *Vertical value networks*, including supplier networks, channel and customer networks, channel and customer networks and vertically integrated value systems. The main goal of these networks is to increase the operational efficiency of their underlying value system.

- *Horizontal value networks,* covering several modes: competition alliances, resource/capability access alliances, resource and capability development alliances, market and channel access/cooperation alliances, ''networking forums'' (company or institutionally driven). These networks are characterized by competitor relationships and cooperative arrangements involving various institutional actors (government agencies, industry associations, research institutes and universities) that aim either to provide access to existing resources or to co-develop new resources.

– *Multidimensional value networks (MDVN)* including ‘‘core or hollow organizations,’’ complex business networks and new value-system networks. For this type of networks three levels are identified: the basic level contains a hub/core organization that creates its market offer by integrating the products and services required from a group of different types of suppliers and channel firms; the medium (more complex) level requires the knowledge and development capabilities of several actors; in extreme level networks are formed to create new technologies or new business concepts, requiring the orchestration of several actors and the creation of new value activities.

The typology developed by Valkokari et al. (2007) is structured around the existence of three different types of networks: traditional, enhancing and innovation networks. For each network type, the author identifies the knowledge management challenges at different stages of organizational knowing (see Table 2).

Table 2: Knowledge Management challenges at different stages of organizational knowing in different types of SME networks (Source: Valkokari et al., 2007)

	Types of Networks		
	Traditional Supply Networks	**Enhancing Networks**	**Innovation Networks**
Sense-making and common knowledge base	✓ Sustain client satisfaction and operational effectiveness. ✓ Increasing specialization of each partner's knowledge base.	✓ Sharing the common vision and management views.	✓ Focus on future business opportunities and changes in Environment. ✓ Broadening of the knowledge base of each partner.
Knowledge creation and innovation	✓ Continuous improvement and performance measurements in network. ✓ Adapt to environmental changes.	✓ Common problem solving and value – creation processes as network. ✓ Business process development.	✓ Continuous and disruptive innovation. ✓ Co-opetition (co-operation between the competitors).
Knowledge sharing	✓ Distribution of production and product specifications, delivery and logistics information. ✓ Efficient mechanisms knowledge integration (direction and routine).	✓ Exploitation of ‘‘communities of practice’’ and learning networks.	✓ Exploration of knowledge on new business opportunities. ✓ Highly differentiated knowledge bases challenge the absorptive capacities.
Decision-making and network governance	✓ Rules and practices made by the focal company open books, sharing the cost information. ✓ Use of common information systems	✓ Common rules and Practices of joint-development and co-design. ✓ Commitment to network and culture of collaboration.	✓ Entrepreneurial and emergent strategies. ✓ Social networks and inter-personal relationships.

2.2.2. Supply networks

Our research focuses on a specific network type: traditional supply networks. In the case of the automotive industry these networks are known to have extremely high levels of productivity and efficiency. Nevertheless they are having more and more problems in dynamically responding to market requirements and to changes in the production environment or to problems occurring during the production process. Most of these problems are related to the complexity (network dimension) and configuration of these networks (connections between network members), particularly with the involvement of an increasing number of SMEs or micro enterprises) and their fragmentation and physical distribution (Kaipia et al., 2007; Reichhart, 2005).

When this research work started our focus was on supply chains of SMEs. We aimed at developing methodologies to help providing higher levels of flexibility and collaboration in complex supply chain networks, allowing the increase of competitiveness, particularly in the case of SMEs. Due to their structure and weaknesses, SMEs currently have a considerable difficulty in surviving and in being successful. Therefore our initial goal was to create a methodology for supporting supply networks coordination activities, through a collaborative platform guaranteeing higher levels of visibility and information sharing among the supply network partners, and a set of tools that could help these companies to succeed.

The literature review somehow changed the scope of our research interest, making us move from supply chains of SMEs to supply chains with SMEs. To develop a successful project, strongly and directly linked to the requirements of SME, we have searched for a representative pilot company. However after some contacts and meetings, we concluded this type of companies have clear difficulties in "changing" and that in the automotive industry environment, SMEs normally do not play a very relevant role, rather being a kind of "passive" element of supply chains.

We have therefore directed our interest towards modern Supply Chains, characterized by globalization (dimension of network), increased use of outsourcing, reduction of the supplier base (single sourcing), *leanness* (e.g., reduced buffers, low inventories, lead times, and lot sizes), increased demand for *just-in-time* deliveries in shorter time windows/lead times, agility, shorter product life cycles and a huge number of partners. However some of these trends in modern supply chains tend to make them more unstable and vulnerable.

2.3. Supply Chain Management

A Supply Chain might be defined as a network of organizations that are involved, through upstream and downstream linkages, in different processes and activities that produce value in the form of products and services for consumers. A typical supply chain can be defined as an integrated process wherein a number of various business entities such as suppliers, manufactures, distributors and retailers, work together. When they work effectively and efficiently modern supply chains allow goods to be produced and delivered in the right quantities, being in the right places, at the right time in a cost effective manner.

In general supply chains (SC) are different from each other, in several aspects. Each has its own unique set of characteristics (e.g., market demand, or operating challenges). The decisions taken in a supply chain, individually (i.e., by each single partner) or collectively, are related to five different areas: production, inventory, location of facilities (the design of the network), transportation, and information. The correct definition of the strategy for these areas will define the capabilities and effectiveness of a company's supply chain (Hugos, 2006).

Mentzer et al. (2001) define Supply Chain Management (SCM) as the systemic, strategic coordination of the traditional business functions and the tactics across these business functions, within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain (containing all activities associated with the flow and transformation of products from the raw-materials until the customer) as a whole (Vachon et al., 2002; Milgate, 2001). In this research project several different factors that influence the supply chain performance will be analyzed.

As previously referred we have considered as a basis for our work in Supply Chain Planning, three main steps, namely:

- *Network Design:* This involves decisions about the number, location, size and mission of manufacturing plants and warehouses, as well as the distribution and the sourcing processes (subcontractors and 3PLs) of a company (or a set of collaborating companies), in order to provide goods to customers. It also involves decisions related to the selection of suppliers (Klibi et al. 2010). The global goal is therefore to determine the physical configuration and the supporting infrastructure of a supply network. In a graphic representation of these networks normally, the nodes are the facilities that are connected by links/arcs that represent direct transportation flows.

- *Inventory Position and Management:* Consists in the definition of the distributed location of stocks and of the inventory policy.

- *Resources Allocation:* It is the process of coordinating and allocating production to resources and defining distribution strategies, to maximize profit or minimize system-wide costs.

This process aims at minimizing annual system costs (production, purchasing, inventory, facility, transportation, etc.), maximizing profit or maximizing the expected net present value of the global operation.

The main goals of this planning process are: to find the right balance between inventory, transportation and manufacturing costs; to match supply and demand under uncertainty by positioning and managing inventory effectively; and to use resources efficiently in a dynamic environment (Simchi-Levi et al. 2003).

In general, Supply Chain Management can be viewed as a key factor for increasing organizational effectiveness and for better achieving organizational goals (competitiveness, customer service, profitability).

2.4. The automotive industry

Supply chain networks in the automotive industry can be significantly more complex than in other cases, due to their hierarchical structure, organized around an upstream planning system, and working top-down from the OEM (Original Equipment Manufacturers) to its suppliers. Usually these networks involve up to 5 levels: a) tier 3, supplying raw materials to the network; b) tier 2, providing modules and component parts to the first-tier suppliers; c) tier 1, integrating full systems, e.g., a seat for direct supply to OEMs; d) OEMs; and e) final customers. There is another characteristic that greatly increases complexity – the worldwide locations (global supplying and sales regions).

Companies need therefore to pay attention to several "international" issues with a strong impact on multinational networks, such as exchange rates, income taxes, access to resources, transfer prices and so on. These elements may significantly increase the uncertainty associated with demand, leading to a relevant bullwhip effect (Ma et al., 2012). Klug (2012) has investigated supply chain dynamics in the automotive manufacturing context and reviewed problems that are also related to the bullwhip effects, particularly in assembly operations.

The automotive industry is a globalized industry characterized by high precision and advanced technologies, a high degree of integration, a product development cycle between 3 and 4 years (from idea to market), a production with hundreds of suppliers from different types of industries (e.g., plastics, metal, petrochemical, rubber), products with thousands of components of different dimensions, high complexity, and a wide range of technologies.

Moreover the players in this sector have to take into account government regulations about safety and environment, possible incentives to investments, the pressure for modernization and for green innovations. And obviously, as a major goal, they need to focus on customers' requirements that are the "engine" of markets. Veloso (2000) argues that all OEMs are constantly under pressure to identify consumer preferences, national biases and new market segments where they can gain market share. Their future in the industry is determined by the ability to adapt and to change operations with minimum damage in time, cost, resources and performance, in other words, by the way the system reacts to uncertainty – flexibility.

Separately, some of these characteristics are common to other sectors, as for example aeronautics and electronics, but the specificity of the automotive industry comes from the cohabitation of all of them in the same sector.

Nevertheless, there are some other specific, distinctive characteristics of this industry, such as the following:

- Firms are extremely concentrated, with a rather small number of giant companies. This feature can be explained by the particular "nature" of the product: for an automotive company to be profitable and reach significant economies of scale, it is fundamental to produce cars in a massive way; moreover the business requires huge initial investments of capital, particularly in equipment and materials (Sturgeon et al. 2009).

- There are strong regional-scale structure patterns of integration, leading to the existence of "clusters". These have emerged naturally due to the requirements and high complexity of the final product, leading to an increase of R&D and innovation activities in terms of design and processes to manufacture sophisticated modules and components. Geographic proximity allows better integration and collaboration between all partners of the supply chain network. The structure of this industry also encourages companies to specialize and develop their own "know how" through mutual co-operation, and to become integrated in the R&D process, as a way to supply customized system solutions to OEMs. The cluster structure is a way to respond to the changes in the value-chain architecture (Jaklic et al., 2005). This also influences the reduction of delivery times facilitating just-in-time production and increasing the system flexibility. The locations of OEMs are widely dispersed throughout the world, possibly far from actual or potential markets.

- Sturgeon et al. (2009) referred another distinctive characteristic: the non-existence of many generic parts or subsystems that can be used in a wide variety of end products without extensive customization, because they tend to be specific to particular vehicle models.

These specific characteristics of the automotive industry raise some interesting, challenging issues that motivated this study and the definition of a case study in this sector.

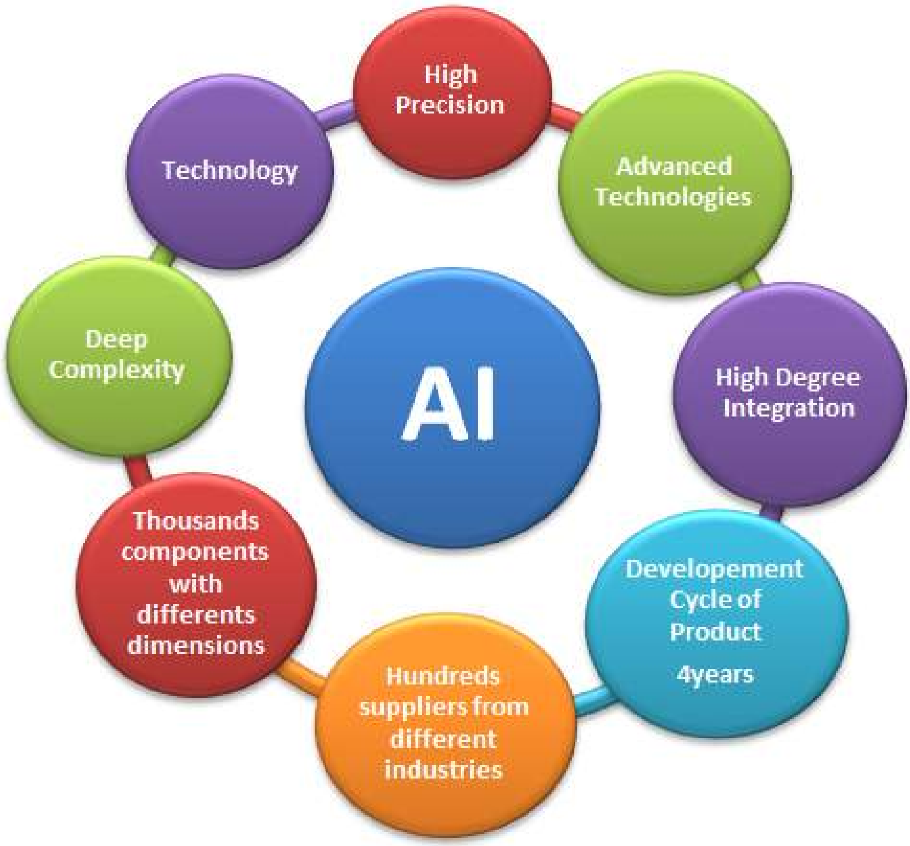


Figure 6: Characteristics of the automotive industry

Supply Chain Networks in the automotive industry are recognized as having extremely high levels of productivity and efficiency. Nevertheless they are having more and more problems in providing an effective, dynamic response to market requirements, and to changes and problems occurring often during the production process. Most of these problems are related to the complexity (network dimension) and configuration of these networks (connection between network members), particularly with the involvement of an increasing number of SMEs and their fragmentation and physical distribution (Kaipia et al., 2007; Reichhart, 2005).

After the 1990s the automotive industry has gone through strong trade liberalization, with large investments by global assemblers. The industry was fostered by investment incentives, national incentives for car purchasing, export incentives, duty drawbacks schemes, and tariffs. We have seen the integration of developing countries into global auto production systems, with suppliers located in multiple regions around the world becoming part of the same supply chain. Globalization strategies of automotive assemblers, suppliers interaction with trade policies, the characteristics of local markets and the integration of production, have been essential to the evolution of the sector and led to a significant increase of the operations complexity. Spatial coordination is therefore requiring higher levels of organizational coordination between assemblers and 1st tier suppliers.

The complexity of supply chain networks can result from several factors such as the network critical dimension, type of enterprises (small, medium or large; development level), variety of products, technological intricacy, organizational systems, geographical location of the links (several supply chains are formed by dispersed companies around the world), or different cultures and languages. Milgate (2001) says "complexity refers to the level and type of interactions present in the system", or in other words, the number of network links and their variety that influence the system's complexity (Beamon, 2003; Milgate, 2001; Simchi-Levi et al., 2003; Vachon et al., 2002).

Moreover in the automotive industry just-in-time delivery imposes additional constraints on the logistics. In part, these issues are solved through physical proximity, but whatever the involved distances are, inventory reduction requires strong coordination of production schedules. The globalization of the automotive industry has increased the complexity of supply chain networks.

As referred above, supply chains in the automotive industry are composed by worldwide companies / facilities, inducing a hard spatial coordination. This coordination is vital in modern supply chains operating in a strong *just-in-time* environment. The conjugation of these factors may significantly increase the complexity of the network. This complexity can be internal (collaboration between different departments of a company) or external (informational, product and service transactions and relations with other network members). External complexity naturally increases with the number of links between entities.

More recently the automotive industry had to face another competitive challenge, namely the development of *green supply chains* and *products*. This implies a "clean" production process (resources extraction, manufacturing process, use and reuse, final recycling or disposal), and an additional concern with emissions legislation and automotive take-back, and with the sustainability of products, processes and markets. Here incentive policies can play an important role (both to industry and to customers). Moreover it is fundamental to establish the right balances between development and possible negative social, economic and environment impacts. In some cases, environmental advantages can bring opportunities for suppliers (Ford, GM and Toyota require from their suppliers a certification related with environmental impact).

2.5. Coordination

For Chopra and Meindl (2001) the supply chain coordination improves if all members of the supply chain take actions together, thus increasing total supply chain profits. In order to be coordinated, the decisions in the supply chain, from retailer to supplier, should aim at maximizing total supply chain profits, and aligning goals and incentives across different functions and stages.

The most common lack of coordination occurs because different members of the supply chain have objectives that conflict, or because information is distorted as it moves across the chain. This distortion of information, when we consider the demand, is the main reason for the occurrence of the bullwhip effect (thus reducing the profitability of the supply chain by making it more expensive to provide a given level of product availability) that results in an increase in all costs in the supply chain and in a decrease in customer service levels. If each member simply wants to maximize its own profit, it will likely not collaborate with the other members to achieve a common objective, and will rather behave as a competitor. So the global results are worse, the customer dissatisfaction increases, as well as the profitability (Chopra et al, 2001; Hugos, 2006; Sheffi, 2007).

The main obstacles to the coordination process in supply chains are multiple, namely: lack of information sharing (e.g., suppliers forecasts are based on received orders, not on expected customer demand), misaligned incentives (optimization of local objectives instead of a global objective), operational inefficiencies (large lots, large replenishment lead times), sales force incentives that encourage forward buying (pricing obstacles), and behavioral obstacles related to a lack of trust.

More recently some companies have been proposing the sharing of sales information, collaborative forecasting, collaborative planning, the implementation of a single point control of replenishment, improving operations to reduce lead times and lot sizes, and building trust and strategic partnerships within the supply chain. This trust could be achieved by the development of a relationship with mutual benefits, with both parties remaining mutually interdependent and contracts being allowed to evolve over time (Chopra et al, 2001; Sheffi, 2007).

> *"When managing the relationship, flexibility, information sharing, visibility of effort and performance of each part, and fairness on the part of the stronger party when distributing costs and benefits help foster trust and facilitate coordination in the supply chain." (Chopra and Meindl, 2001)*

Hewlett-Packard (HP) is a well known case study related with coordinated product and supply chain design, given by several researchers as a good example to illustrate the power of coordination. HP has a complex and worldwide supply chain, needing to address the problem of finding the best way to satisfy customer needs in terms of product availability while minimizing inventory; and how to get an agreement among the various parties on the right levels of inventory. The answer to this particular problem was achieved by a strong process of coordination between international companies in the USA and in Europe, showing the strong impact of a well performing supply chain, together with the most efficient production techniques and product design processes, such as standardization. The company managers developed a product design that reduced logistic costs (more efficient design in terms of packaging and storage), with production processes having multiple steps that could be completed in parallel, thus reducing lead time (and consequently the levels of inventories).

Trust is a key issue identified in the literature by several researchers, as being the basis of success in a process of coordination. Kumar (1996) showed, in a study with the title

“The Power of Trust”, the benefits generated by trust, in the case of the relationship between Procter & Gamble (P&G) and Wal-Mart. Fear and intimidation used to be frequent between partners of the same supply chain, but this is obviously not the most effective way to achieve supply chain profits.

These two companies developed a partnership that has become the benchmark for manufacturer-retailer relationships. It is based on mutual dependence: Wal-Mart needs P&G’s brands and P&G needs Wal-Mart’s access to customers. The relationship took time, more than a decade, to mature and has gone through its share of growing pains, but mutual trust has been instrumental in the companies’ development of an effective long-term relationship. They trust enough to share sales and price data, or to give away some control of the order process and inventory management. This case study clearly shows that trust contributes to maximizing the profits of both companies.

2.6. Collaboration

A collaboration relationship between all entities of the supply chain network is fundamental. It allows real time, higher quality information sharing between companies, with decreasing materials costs, minimizing stocks, reducing information errors, and decreasing shortages (Milgate, 2001; Simchi-Levi et al., 2003; Vachon et al., 2002; Kapia, et al., 2007).

Anthony (2000) stated that “supply chain collaboration occurs when two or more companies share the responsibility of exchanging common planning, management, execution, and performance measurement information. Collaborative relationships transform how information is shared between companies and drive change to the underlying business process”. In this process the relationship between people is very important as it involves personal characteristics (e.g., to use appropriate vocabulary so that the information interpretation is correct; easiness of relating with other people) (Truong et al., 2003).

Govil et al. (2002) describing Daimler Chrysler (one of the largest automotive manufacturers in the world) have identified how important and powerful a fair collaboration between partners is and how it can improve the efficiency and benefits of each partner in the long term. Their study concluded that a perfect supply chain requires a strong collaboration between all the members, from the suppliers to the final customers. But without a clear definition of the collaboration rules this task could be hard, especially if the concerned members are rivals or competitors.

According to Kapia and Kallionpaa (2007), and Reichhart (2005), a higher level of complexity influenced by configuration of the networks prevents collaboration. Choi and Hartley (1996) studied the automotive industry and concluded that this industry has reduced the supply chain size to increase its reliance on the suppliers and the collaboration with them (thus developing closer relations).

2.6.1. Modes of Collaboration

Pisano and Verganti (2008) have characterized the different types of collaboration. These authors identified 4 basic modes of collaboration, each characterized by distinct trade-offs of two criteria: type of participation and type of governance. The network participation can be *open* (everyone can participate) or *closed* (like private clubs,) and the network participation can be *hierarchical* (one partner decides about all issues) or *flat/nonhierarchical* (the partners share the power to decide about key issues).

Table 3 shows the four ways to collaborate, with some examples, presenting their advantages, disadvantages, as well as the enablers of each type of collaboration used in the classification.

Table 3: The four ways to collaborate (source: Pisano and Verganti, 2008)

Innovation Mall A place where a company can post a problem, anyone can propose solutions, and the company chooses the solutions it likes best. ***Example:*** *The InnoCentive.com website, where companies can post scientific problems.*	**Innovation Community** A network where anybody can propose problems, offer solutions, and decide which solutions to use. ***Example:*** *Linux open-source software community.*	**PARTICIPATION**	**OPEN**	**Advantage:** The company receives a large number of solutions from domains that might be beyond its realm of experience or knowledge, and usually gets a broader range of interesting ideas. **Challenge:** Attracting several ideas from a variety of domains and screening them. **Enablers:** The capability to test and screen solutions at low cost; information platforms that allow parties to contribute easily; small problems that can be solved with simple design tools, or large problems that can be broken into discrete parts that contributors can work on autonomously
Elite Circle A selected group of participants chosen by a company that also defines the problem and picks the solutions. ***Example:*** *Alessi's handpicked group of 200-plus design experts, who develop new concepts for home products.*	**Consortium** A private group of participants that jointly select problems, decide how to conduct work, and choose solutions. ***Example:*** *IBM's partnerships with select companies to jointly develop semiconductor technologies.*		**CLOSED**	**Advantage:** The company receives solutions from the best experts in a selected knowledge domain. **Challenge:** Identifying the right knowledge domain and the right parties. **Enablers:** The capability to find unspotted talent in relevant networks; the capability to develop privileged relationships with the best parties.
GOVERNANCE				
HIERARCHICAL	**FLAT (Nonhierarchical)**			
Advantage: The company controls the direction of innovation and who captures the value from it. **Challenge:** Choosing the right direction. **Enablers**: The capability to understand user needs; the capability to design systems so that work can be divided among outsiders and then integrated.	**Advantage**: The company shares the burden of innovation **Challenge:** Getting contributors to converge on a solution that will be profitable to the company. **Enablers:** Processes and rules that drive parties to work in concertation to achieve common goals.			

For each of these modes of collaboration there is a group of guidelines for implementation and improvement. In our research we clearly have a *closed* and *hierarchical* network. In this collaboration mode (called *elite circle*), one company selects the participants (partners), defines the problem, and chooses the solutions. This is appropriate when the company masters the knowledge domain, from which the best solutions to problems are likely to emerge, and when it is important to have the best experts and they are available. In this case, the company can define the problem and evaluate the proposed solutions. In the automotive industry this is frequent: OEMs develop the main concepts but the details are developed in collaboration with a set of selected members (suppliers) with know-how in each of the components required to build the new product.

A collaborative network in which intense collaboration is practiced among its members is called a goal-oriented network. This type of networks can be further divided into: *grasping opportunity driven networks* (a collaborative network driven by the aim of grasping a single opportunity and that is dissolved after the goal is accomplished), and *continuous production driven networks* (a collaborative network driven by or oriented to continuous production / service provision activities). Supply chains are in this latter group.

A *Supply Chain* is a stable long-term network of enterprises each having clear roles in the manufacturing value chain, covering all steps from initial product design and the procurement of raw materials, through production, shipping, distribution, and warehousing until a finished product is delivered to a customer.

Collaborative Transportation networks are also a type of continuous production driven networks. These are long-term collaborative networks involving a diversity of actors such as road management entities, logistic operators, parking management entities, gas stations, banks, and others, organized to provide integrated transportation services.

2.6.2. Motivations for collaboration and potential benefits

To develop collaboration forms between members of a supply chain some favorable conditions are required that are related with human resources (common values, to have exchanged experiences), finance (to be financially healthy, to invest in common network resources), social relations (to have trust in the network partners), technological platforms, organization and management.

Collaboration allows a faster access to new markets, without high investments, and can be viewed as a way to create more business opportunities and to increase market share. When we consider networks created to develop a new product, several benefits can be identified, from sharing and reduction of costs and risks, to the reduction of development time, improved skills and knowledge, increased innovation capability and higher access to resources. Furthermore companies can give more attention to their resources on critical activities leading to increased specialization. The benefit of costs reduction is also influenced by the reduction of the inventory, increased profitability and efficiency.

As referred above, collaboration is an important process in which network partners can exchange information, share resources, knowledge and responsibilities, aiming at achieving a common goal. This process may be complex and difficult to conduct, but it can often mean the company's survival, or represent significant economical advantages.

The interaction among partners also speeds up the system reaction to uncertainty, or in other words, companies increase their flexibility and agility. Consequently customer service is improved (e.g., there is a reduction in lead time or in the number of customer complaints). Moreover, the collaborative process gives companies the opportunities to learn, to develop creative solutions, to increase specialization, to enhance the quality of products and of production processes. Therefore in some sense, by collaborating companies become more independent. This was probably the main reason for us to include collaboration concerns in this research work.

Although collaboration in networks may have several associated benefits, sometimes companies have to face significant difficulties in forming these networks. The main factors that can be barriers to the collaboration between organizations are: the lack of collaboration experience, the lack of appropriate infrastructures or resources, the need for an initial investment, the geographical distance, the need to create a trust climate, the risk of losing a competitive and autonomous position, the loss of technological superiority, the need to identify organizations with the appropriate competences and the appropriate information systems.

2.7. Uncertainty

A global supply chain network involves several countries and consequently it becomes fundamental to take into account various factors related to internationalization, such as tariffs, exchange rates, customs duties, income tax legislation, national production resources, transfer prices, government policies, trade barriers and competition. Some of these factors may significantly increase the *uncertainty* in a supply chain network, but they are surely not the only ones.

Other frequent parameters of uncertainty are product-market demand, raw material prices, energy, labor, production, and transportation costs (with price variability) and lead times. Klibi et al. (2010) argue that *extreme events,* such as natural disasters or terrorist attacks, should also be taken into account as uncertainty.

We illustrate the importance of taking uncertainty into consideration through an example: the case of unknown market demand behavior. This is a crucial issue in designing a supply, as it gives us a "clue" about future markets, about sales or production volume requirements by geographic zone, and about how to match demand with supply. For example, when demand is seasonal we need to order raw-materials in advance based on forecasts, see for example the case study of "NFL replica jersey - Reebok" (Parsons, 2004). It is vital to plan the inventory before the season begins and during "the chase", a period of demand spike based on “hot players” and unexpected team success on the baseball field.

On the other hand, we have the problem of defining a new location for production sites that should go on being profitable after some years, and not only for a short period of time. We should therefore take also into account that the expected return on the initial investments is also influenced by uncertainty during a long period of time. To decide on a new location taking exclusively into account the current demand may be a big mistake. Stochastic optimization models are one natural way to deal with uncertainty.

In Table 4 the main uncertainty factors identified in the literature are summarized.

Table 4: Uncertainty factors

	1	2	3	4	5	6	7	8
Demand	X	X	X	X	X	X	X	X
Supplies			X					X
Resource Capacity			X					
Production Costs			X	X			X	
Exchange Rates	X	X						
Transportation / Lead Times								X
Transportation Costs			X		X	X		
Duties	X							
Price (Products, Raw Materials)				X				
Extreme Events								X

References: [1] Fleischamn et al. (2006); [2] Kauder and Meyer (2009); [3] Santoso et al. (2003); [4] Alonso-Ayuso et al. (2003); [5] Vidal and Goetschalckx (1997); [6] Perez eta al. (2005); [7] Yu and Li (2000); [8] Klibi et al. (2010).

As shown in Table 4, demand uncertainty is the most often considered factor, but in many papers that is not the only one. Usually, models include 2 or 3 uncertainty parameters. However, uncertainties related with costs are also frequent in mathematical models. More recently Klibi et al. (2010) introduced the importance of considering extreme and catastrophic events as an uncertainty, and they have shown their impact in running supply chains.

The finished product prices, government policies, transfer prices and taxes are also found in the literature as important factors. The “taxes” factor is more frequent in models for domestic supply chains in the United States, due to the difference of taxes among states. Considering “transfer prices” as an uncertainty parameter becomes useful in models with subsidiaries subject to different legislation or currency.

Demand is a factor considered in most of the models, as shown above, even if it is widely recognized how difficult it is to do reliable forecasts and deal with uncertainty in an adequate way. In this context, aggregate forecasts, covering a broader range of products, are often viewed as more satisfactory as they tend to smooth the variability associated to a more fragmented demand. The demand is not the only concern, as uncertainty is also associated to supply (e.g., in terms of the availability of raw materials and components) and competition (concerning, e.g., the strategy and actions of product suppliers in the market). Although demand is an uncertainty factor crucial for the supply chain management, decision makers need to be aware of the market behavior and of the competitors' decisions. These decisions include investments (capacity, infrastructures), the definition of inventory policies, production scheduling and planning, and resource allocation (labor, equipment).

Demand uncertainty is, in the medium term, a key concern of OEMs, but it is probably not so critical for the other members of the automotive supply chain. Analyzing the consequences of the economic crisis in 2008, we can see that the OEMs already had business contracts with their suppliers, in order not to pay penalties, they produce the forecasted quantities. This reaction caused extreme levels of inventory. However, most supply chain partners only felt problems after 6 months (time horizon of fixed forecast).

The performance of the automotive industry may clearly be influenced by several uncertainty factors that can cause strong perturbations in its regular operation and on the viability of supply chains. Perturbations can result from extreme events such as natural disasters, economic crisis, terrorism and inflation (on raw-materials, energy, petrol or labor). These factors can, in a long term perspective, be quite critical.

The most frequent uncertainty factors can be classified in two main groups:

[1] Typical uncertainty factors related with regular unexpected events that, in general terms, can be forecasted and handled with some previously developed mechanisms. These mechanisms can provide companies with a higher level of flexibility. Some examples of these factors are related to: demand, supply, resource capacities, production costs, exchange rates, transportation costs, transportation time, lead times, duties (customs taxes), inflation (on products, raw materials, energy).

[2] Extreme uncertainty factors, normally related to large disruptions in supply chains, and requiring strong mechanisms and complex action plans to recover (this is obviously related to the *resilience* of the company). The impact and the moments when these events can happen are very difficult to forecast. Some examples of this type of factors are: strikes, natural disasters, economic crises, terrorism, wars, epidemics, industrial disputes, sabotage, labor disputes (Sheffi, 2001).

Uncertainty factors can directly or indirectly influence the performance of supply chains. For example, the dramatic events of 11 September 2001 did not directly affect the automotive industry but indirectly they had a strong impact because of the emergence of a new regulation to transport goods across borders, market nervousness, increase of fuel prices, and so on. Ford and Toyota had to stop production in their manufacturing plants in the United States due to significant delays in delivery of parts coming from distant countries (Sheffi, 2001).

Our work is focused on a part of the automotive industry that supply the regular market segments. If we consider higher market segments we will find different behaviors and uncertainty factors that are more related with demand. These products have more customization, a higher value, a pull production and long lead times (this is, e.g., the case of Lamborghini and Maserati chains).

One way to deal with uncertainty and variability could be to control a combination of two factors, as suggested by Chopra and Meindl (2001): production capacity and inventory. From the production capacity side, approaches may involve labor flexibility, with seasonal labor (increasing the labor hired to temporary employment companies), or subcontracting. Inventory is less critical to our research. In general inventory approaches are based on the development of common components across multiple products, or in managing a seasonal demand, but neither of these approaches is applicable to the automotive industry.

In the literature, uncertainty is often related to “the bullwhip effect”. In this research this concept is not directly studied but we should note that “the bullwhip effect” is one of the most common consequences of supply chains dynamics. Small changes in the final product demand, at the front of the supply chain, are reflected into wider and wider swings in demand as experienced by company’ further back in the supply chain. The main factor contributing to this effect is the lack of coordination between the members of supply chain (Simchi-Levi et al., 2003).

It is obvious that uncertainty cannot be eliminated, but by using more comprehensive decision support approaches we can minimize its effect in supply chain performance. Ignoring the effects of uncertainty on the supply chain results in approaches that are unable to adequately handle future changes of the real-world system. These uncertainties are directly related to the *vulnerability* of organizations to *risk.*

2.8. Flexibility

To quickly and efficiently adapt to changes in the environment, many companies have made important investments in increasing the flexibility of their supply chains. Flexibility can be viewed as the ability to adapt, to change or transform with minimum damage in time, cost, resources and performance, i.e., how well the system reacts to uncertainty (Mersechmann et al., 2011). Or in other words, *Supply Chain Flexibility* could be defined as the ability to accommodate volume and schedule fluctuations from suppliers, manufacturers and customers. This is a vital component to Supply Chain success and defines how well the system reacts to uncertainty.

Flexibility allows reductions in the number of backorders, lost sales and late orders, and it is also a way to increase customer satisfaction and the ability to respond (seasonality, machine breakdowns, and poor suppliers performance). (Beamon; 1999)

Slack (1987) identified four different types of flexibility: *product flexibility* (the ability to introduce new products or to make alterations to existing ones, to change the output level as a reaction to variable demand), *mix flexibility* (the ability to modify the range of products made within a given time period), *volume flexibility* (the ability to change the level of aggregated output) and *delivery flexibility* (the ability to change planned or assumed delivery dates). But, in the context of our research project the main flexibility types are related to volume, delivery and product mix.

The relation between network complexity and the difficulty in getting global flexibility in supply chain networks was identified by Garavelli (2003) and Sawhney (2006). The flexibility level of each network link (internal and external complexity) naturally influences the global flexibility of the supply chain network. Sometimes, the network variability (companies with different characteristics) is critical for reaching higher levels of global flexibility in supply networks.

Flexibility is also linked with labor and technology (Reichhart, 2005). A company has labor flexibility by training its employees to perform several different jobs (versatile employees) (Sawhney, 2006). And technology flexibility is associated with the capacity to transmit the information (by software and phone). Joshi (1998) identified “real time visibility as one of the crucial factors for efficient supply chain management”. Nowadays, companies feel the need to provide higher *visibility* of correct information in the supply chain network, and to have real time information updates, as a way to improve efficiency and to optimize costs. Moreover the capacity to transmit information along the supply chain seems to be directly related with the coordination between all network members.

Increased visibility over the global network can be critical for some key partners in the processes (in particular for first tier suppliers). This visibility is surely a way to guarantee flexibility and fast response to unexpected events or changes in the demand.

To achieve higher levels of information visibility and coordination among business partners is in fact the key for enhanced flexibility. Managing capacities and capabilities, improving the level of collaboration in planning logistic activities and in operations management is also critical for achieving that required flexibility (Sawhney, 2006; Simchi-Levi et al., 2003).

Obviously information technologies are not the answer to all supply chain problems. Human resources or the cultural environment are also crucial for their success. Fawcett et al. (2005) concluded that information technologies and the people that use them are two critical factors for companies’ success. They state that the “managers must take into consideration organizational culture and the education and training of employees to facilitate supply chain collaboration and success”.

Collaboration with suppliers is also vital in uncertainty environments and can directly influence the capability of the organization to be flexible.

In environments characterized by a high level of uncertainty companies with highly flexible supply chains in general perform better than companies with less flexible supply chains. However in "certainty" environments the opposite often holds.

From a strategic point of view, supply chain flexibility enables a company to respond more quickly to changes in supply and demand. But in practice it is essential to adequately balance the benefits and the costs of flexibility. "How much flexibility is really needed in a given, specific situation?" To choose the right degree of supply chain flexibility is crucial. Some automotive supply chains achieve flexibility with safety stocks that imply higher costs and additional labor.

2.9. Risk Management and Resilience

2.9.1. Risk Management

In these environments characterized by high levels of complexity and uncertainty, another important issue associated with supply chains is the *vulnerability* to risk,. Mitchell (1999) defined *risk* as a subjectively determined expectation of loss. Risk is directly associated with uncertainty, with more exposition to risk implying more uncertainty (Manuj and Mentzer, 2008).

Supply Chain Risk Management deals with quite different types of risk that can be: internal to the company (process, control), external to the company but internal to the supply chain (demand, supply) and external to the network (environmental). So, risk is directly related with vulnerability to losses or damages. It is associated with a probability (of the occurrence of a given event) times a degree of severity (negative business impact).

In 2009, Rao and Goldsby reviewed the literature about typologies for supply chain risks. This research identified quite different sources of risk, namely several factors related to the environment, the industry, organizational characteristics, the decision-makers, and problem-specific factors. Tang (2005) views inherent uncertainties as operational risks. These risks are in general related to customer demand, to supply and to costs. These are the typical uncertainties considered in our research. According to the author, the four basic approaches for managing supply chain risks (to improve supply chain operation) are:

a) *Supply Management* issues: supply network design, supplier relationships, the supplier selection process (criteria or approval/selection), supplier order allocation and supply contracts;

b) *Product Management* issues: process sequencing or postponement (make-to-order or make-to-stock system without forecast updating; make-to-stock systems with forecast updating);

c) *Information Management* issues: managing products with short life cycles, managing products with long life cycles (information sharing; vendor managed inventory; collaborative forecasting);

d) *Demand Management* issues: shifting demand across time, market or across products.

These issues need to be tackled with a good support in terms of coordination and collaboration across the entire supply chain.

Risk management can provide firms with significant competitive advantages. It may involve moving production between plants, interchangeable and generic parts in many products, cross-training of employees, using concurrent processes for product development, ramp up and production/distribution, designing products and processes for maximum postponement of as many operations and decisions as possible in the supply chain, or aligning their procurement strategy with their supplier relationships. Developing collaborative relationships with suppliers that are closely associated with a company will in general make those suppliers more likely to be loyal allies during a crisis. But the failure of any of these suppliers can have a catastrophic effect. In a large network we should concentrate our attention in the distribution of risk along supply chain members – *risk sharing.*

Thun and Hoening (2011) developed an analysis focused in supply chain risk management, specific for the automotive industry. After analyzing data from 67 manufacturing companies, the authors concluded that companies with high implementation degree show a better supply chain performance. Furthermore, the results show that the group using reactive supply chain risk management has higher average value in terms of disruptions resilience or on the reduction of the bullwhip effect, whereas the group pursuing preventive supply chain risk management has better values concerning flexibility or safety stocks.

Uncertainty and turbulent markets obviously increase risks in supply chains, as well as their vulnerability and complexity. Risk management policies naturally depend on the nature of the risk. Therefore extreme uncertainty, as described above, requires specific mechanisms and approaches. To face these problems supply chains should be as resilient as possible.

2.9.2. Resilience

First, it should be noted that the types of risks considered as *extreme uncertainty* in our research are sometimes referred in the literature as vulnerability drivers. *Vulnerability* is an exposure to serious disturbance. (Christophers and Peek, 2004; Wagner et al., 2010)

Creating a *resilient supply chain* is naturally a way to manage risks, but increasing resilience in a network requires high levels of collaboration (with higher levels of visibility between chain members), responsiveness (the suppliers' ability to quickly respond to the buying party's needs), agility, creation of a risk management culture and efficient design. *Agility* consists in being able to react quickly to unpredictable events, and it is clearly a distinct advantage in an uncertainty environment.

In the physical sciences, resilience is the ability of a material to recover its original shape following a deformation. In the corporate world resilience is associated with the ability of a company to bounce back from a large disruption. This includes for instance, the speed with which it returns to normal performance levels. So a resilient organization is able to successfully confront the unforeseen, to return to its original state or move to a new, more desirable state after being disturbed. This means a higher capability to deal with disruptions and managing risks, and to be more flexible and adaptable (Sheffi, 2005).

Companies can develop resilience by increasing *redundancy,* developing an extra inventory or using safety stock of materials and finished goods, thus providing companies with time to plan their recovery following a disruption. Underutilized capacity can also be used, by having many suppliers, to develop a "breathing room" to continue operating after a disruption. These are in general temporary and very expensive actions. They imply additional costs and reductions in quality, as shown by *lean* policies. Redundancy is not a good option because we pay redundancy stocks with sloppy operations, extra capacity that decreases quality, and workers that increase costs. The company efficiency is drastically and negatively influenced by these approaches.

Another option is the creation of flexibility to withstand significant disruptions and to guarantee better response to demand fluctuations. More flexibility could be achieved by adopting standardized processes, by using concurrent instead of sequential processes, by planning to postpone, or by aligning the procurement strategy with supplier relationships. As referred above processes such as moving production among plants, creating interchangeable and generic parts in many products, cross-training employees, using concurrent processes of products development, can be developed in parallel as a way to increase agility and to reduce time to market).

Figure 7 summarizes the main uncertainty factors and the main characteristics of a resilient supply chain, as studied in our research.

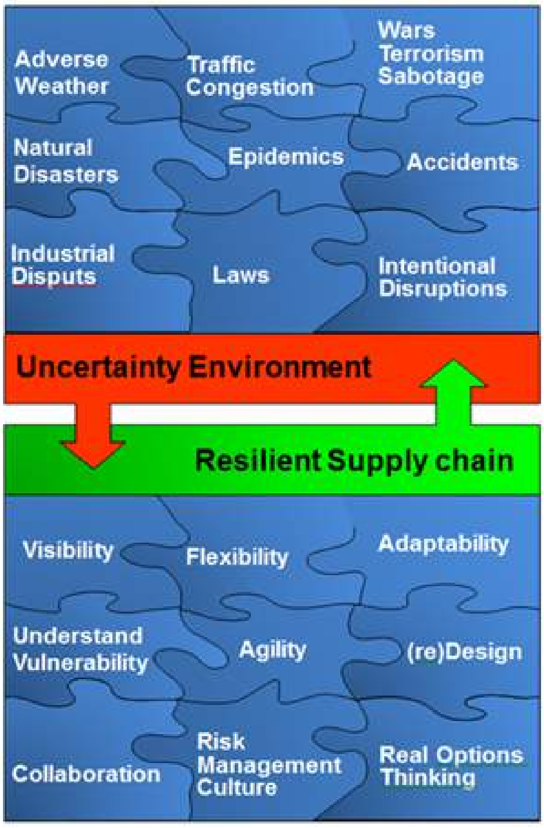


Figure 7: The main uncertainty factors and the main characteristics of a resilient supply chain

As already referred, suppliers that are closely associated with a company are more likely to be loyal allies during a crisis. But serious problems occurring in any of these suppliers can have a catastrophic effect on the whole chain. Modern supply chains tend to promote a close collaboration and interaction with customers and suppliers, but as identified previously these supply chains are, in many aspects, more vulnerable. With a large network we should focus our attention in the distribution of risk along supply chain members – *risk sharing.* Toyota policy is based on sharing risks with suppliers that have stock, even during the innovation processes. The process of choosing suppliers should take into accounts resilience and flexibility issues, customer satisfaction and risk management.

Recently we have been confronted with several examples of strong disruptions of supply chains with a strong negative impact in companies and in the economy, sometimes not only where those disruptions have happened but also with effects on many members of entire supply chains or even several supply chains. These events have been growing in frequency and impact. For example, the Japanese earthquakes of 2012 (resulting in a catastrophic tsunami), the Philips NV fire of 2000 (a disruption with strong impacts on Nokia and Ericsson), the 9/11 terrorist attacks, the Katrina hurricane in 2005, the Icelandic volcanic eruption of 2010. These catastrophes have disrupted supply chains around the world requiring the development of innovative recovery strategies.

Other type of problems that can provoke a strong disruption on chains are insolvency of suppliers or quality problems. Bosch, as a supplier of the automotive industry, faced a severe disruption in 2005 because they failed to detect a defect in a basic component used in injection pumps supplied to automotive OEM. The problem became huge because this component was supplied to a large number of US companies that use this component in their products (Wagner and Bode, 2006).

Norrman and Jansson (2004) describe some examples of risk sources and some supply chain rippling effects. They analyze the impact of hurricane Floyd that flooded a Daimler-Chrysler plant producing suspension parts in Greenville, North Carolina (USA). As a result, 7 other companies across North America had to be shut down for a week. The foot-and-mouth disease in the UK in 2001 affected the agriculture industry more than its last outbreak 25 years ago. This happened because former local and regional supply networks had become national and international, and the industry was much more consolidated (Jutter et al., 2002). Volvo and Jaguar have also stopped the production due to the lack of quality of a leather supply. Ericsson is a well-known case study on the consequences for the business of a fire in a supplier. But Toyota also had significant problems with a fire when they have been forced to shut down 18 plants for almost 2 weeks following a fire in February 1997 at its Asian brake-fluid proportioning valve supplier, Seiki.

Cultural changes are also vital in the process of achieving a resilient supply chain. These changes involve continuous informal communication among employees, empowerment so that teams and individuals are able to take the necessary actions, when disruptions occur. Culture is difficult to define and even more difficult to change.

2.10. Decision Types

Until now we have discussed several related concepts required to develop and manage a supply chain in an efficient way, to maximize profits (or minimize costs), taking into account the involved dynamics. Some of these concepts are related with decision-making, a central issue in this research, with information sharing, and with coordination and integration issues.

To structure and simplify the process, decisions related to Supply Chain Planning are considered to occur at three hierarchical levels: strategic, tactical and operational.

[1] The **strategic level** involves a time horizon of more than 1 year and decisions about the configuration of the network (production topology; the number, location, and capacity of facilities), product selection, product allocation among plants, and vendor selection for raw materials. Decisions at this level require a large investment in capital over long periods of time.

[2] The **tactical level** involves decisions about the aggregate quantities and material flows for purchasing, processing, and distribution of products. It aims at

obtaining a best utilization of the available resources. These decisions are focused in medium term time periods, from 1 month to 1 year.

[3] The **operational level** has a short time horizon (e.g., 1 hour, 1 day or 1 week) and typically it involves decisions related with master production scheduling, e.g., production volume, transportation orders, and purchase orders (Landghem and Vanmaele 2002; Santoso et al. 2005; Alonso-Ayuso et al. 2003; Dogan et al. 1999).

Such decisions can be made with models with single or multiple periods, and these models can be deterministic or stochastic (i.e., they can explicitly consider uncertainty parameters).

Decision variables are in fact those variables that within a model one can control, and they should reflect the alternatives for decision-making at the different levels of the planning process. The variables that are more often referred in the literature are related with:

- *Production:* quantity, allocation, configuration, BOM (Fleischman et al. 2006; Kuader et al. 2009; Alonso-Ayuso et al. 2003; Vidal et al. 2001; Dogan et al., 1999; Yu and Li 2000; Arntzer et al. 1995; Cohen et al. 1989);

- *Investment:* on capacity expansion, on facilities (Fleischman et al. 2006; Kuader et al. 2009; Santoso et al. 2005; Dogan et al. 1999);

- *Stock:* level, allocation, number of products (Alonso-Ayuso et al. 2003; Dogan et al. 1999; Yu and Li 2000);

- *Transportation*: volume, routes, costs, mode (Alonso-Ayuso et al. 2003; Santoso et al. 2005; Vidal et al. 2001; Perez et al. 2005; Dogan et al. 1999);

- *Flexibility:* reserve of capacity production or product units (Fleischman et al. 2006).

The decision variables of each model are chosen not only to allow the optimization of the performance measures of a supply chain, thus determining the efficiency and effectiveness of a current system, but also to compare competing alternative systems, as well as to design new systems (based on the values of decision variables that yield the required level of performance). Beamon (1998) identifies two main categories of quantitative performance measures: based on costs (operational costs and investments), on the one hand, and based on customer responsiveness, on the other hand. Qualitative performance measures are also important in some circumstances – this is the case of customer satisfaction, flexibility (capacity to answer to random fluctuations in the demand) as well as information on material flow integration (Beamon 1998).

Therefore in the context of our work the following decisions should be considered: the location of new facilities; changes to existing facilities concerning their production capacities and stocking; sourcing decisions (advanced warehouses); allocation decisions (what markets should be served by which warehouses; products/plants).

To decide about "where to produce" we will take into consideration the operational costs (transportation and production). Additionally we need to be concerned with some practical issues/options such as advanced picking, constraints of proximity to OEMs (Just-in-Time restrictions), dimension of nearby markets, or where to locate stocks (Figure 8).

In the automotive industry the choice of a supplier is a very complex process involving several non-tangible factors, and therefore in this work, we will not consider it as a decision variable.

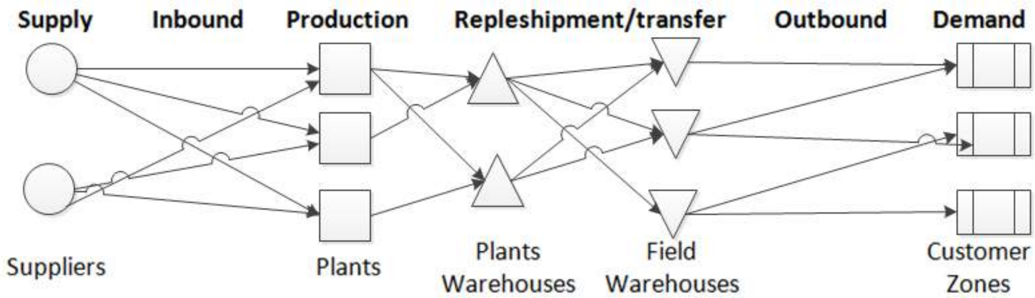


Figure 8: The Supply Chain structure in our research

All these decisions are influenced by the presence of large uncertainties about the operational conditions and the supply chain dynamics. Investments can be extremely large, and are often irreversible. For this reason it is crucial to take into account aspects related to time, space and resource availability. Moreover, in order to maximize the return on investments, a clear assessment of the present business level is required, and its potential in future years has to be estimated.

Our model should support decision-making on systems design (configuration of the network, product allocation), on investments (capacity or new facilities/links) and on the transportation network. Moreover, to keep research as applied as possible and grounded on the case study, we could not neglect the complexity of the network (globalization), (typical and extreme) uncertainties, the objectives of each network member (conflicts, trust, collaboration, coordination), and system evolution/variation over time. (i.e., the dynamic nature of the supply chain).

2.11. Conclusions

The financial crisis has clearly shown the vulnerability of our global economy. Around the world we could witness a strong decline in industrial production. In this context, industrial organizations set their efforts more and more on the control and reduction of costs, not only as a way to fight a growing market competition but also to overcome the problems posed by the current global economic and financial crisis. One of the main goals of our work was to pursue research strongly aligned with the concerns of industry and to develop tools to help in the recovery of markets.

The automotive is one of the most affected industrial sectors, facing a consistent decrease in the sales of vehicles and an increase of the prices of oil and steel. Supply chain management can play a prominent role in improving the performance of this sector, by enhancing systems already in place or by designing and implementing new systems. In this industry supply chain design strongly depends on the dynamics of markets that lead to high levels of uncertainty. This aspect has been often neglected in the literature. There is a few models related with automotive supply chain networks and basically they are all deterministic, not giving the right attention to uncertainty factors.

The main objective of our work is fulfilling this gap by proposing a model that explicitly considers the risk directly associated with uncertainty factors. The developed stochastic model takes into account the specific features of the global modern automotive supply chain and it aims at supporting strategic and tactical decision-making (design, investments and transportation network).

Our work also approaches two types of uncertainties – *extreme* and *typical*. Extreme uncertainties are related to strong disruptions of supply chains, that require a resilience capability of companies to recover. Typical uncertainties are less problematic when the supply chains have a *risk management* process implemented, supported by tools that provide the supply chain with the flexibility required to adapt quickly and efficiently to changes in the environment. Flexibility is improved by the capacity of adaptability, collaboration and visibility across the supply chain.

Figure 9 is a map summarizing our literature review and shows the path we have followed in defining our research project.

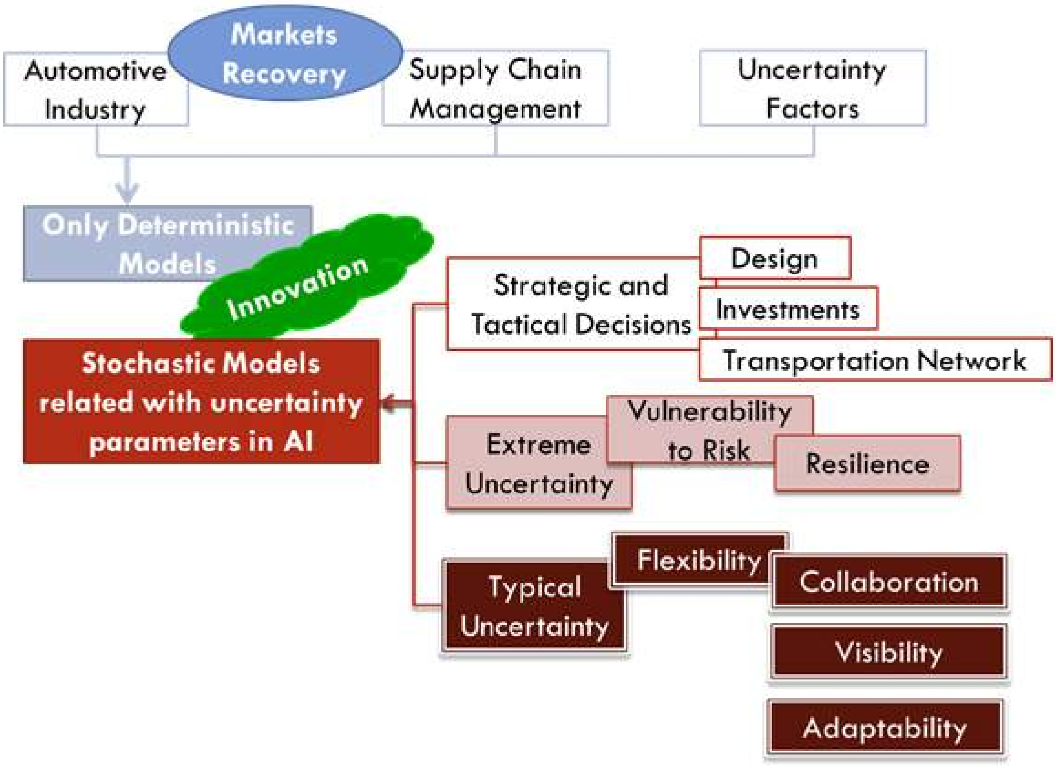


Figure 9: Research Project Concepts

3. Existing models and opportunities for research

In the previous chapter, we have presented the most important issues involved in our research, with a special focus on the concerns that originated this doctoral project. Having established a connection between these concepts, we aim at developing a "practical tool" to work with the relations, concepts and data described. More precisely we want to develop an Optimization Model.

As described by Shapiro (2001), optimization models provide a rich and robust framework for combining data, relationships, and forecasts from descriptive models. The optimization models provide managers with broad and deep insights into effective plans, which are based on the company's decision options, targets, objectives, constraints and commitments. In our work we use a natural extension of linear programing models - Mixed Integer Programming (MIP) models, characterized by different types of variables: integer, continuous and binary variables. Linear programming only deals with continuous variables and in supply chain models binary variables are essential to decide for example if we open or not a facility (thus reflecting the combinatorial nature of these problems). Binary variables are typically associated with strategic network design decisions, such as those that are related with locations or capacities. Continuous variables are connected with tactical and operational decisions associated, for example, with material flows (Melo et al., 2009). These are the main reasons to use mixed integer programming.

MIP models provide a rigorous approach to supply chain analysis capturing the important decision options, constraints, and objectives. These models are capable of finding demonstrably good solutions and can yield optimal solutions if the decision maker is willing to wait long enough for the algorithms to identify them. In fact, binary variables are used to model the combinatorial aspects of decision problems that are intrinsically difficult and require the recourse to very time consuming methods (such as LP based branch-and-bound methods).

For the type of problems under analysis, models and solution methods differ in various dimensions, such as the number of periods in the planning horizon, types of uncertainty, objectives, or decision variables.

For supply chain design, we have seen in the last decade a considerable development of deterministic models, which are becoming more and more comprehensive and detailed. More recently, and in an attempt to bring more reality into their models, researchers have included parameters for uncertainty, mainly related to demand and cost of raw materials, thus developing stochastic models

In the context of our research, to solve strategic or tactical supply chain problems, we are going to analyze both deterministic and stochastic mathematical programming models. Other approaches might also be considered, such as economic based or simulation models, but they are outside the scope of this work. Thus, our objective is to use mathematical optimization techniques that include exact algorithms (guaranteed to find optimal solutions) and heuristic algorithms (that find good, not necessarily optimal, solutions in useful time).

The following sections present some relevant deterministic and stochastic models from the literature in the area, as well as other important information identified as relevant to this doctoral project. The literature reviews by Beamon (1998), Snyder (2006) and Melo et al.(2009) were very useful in developing a plan to perform a comprehensive literature search and analysis.

3.1. Variants and scope of models

Based on the number of time periods of the planning horizon, a decision model can be classified as static or dynamic. Static models are also called single-period models, as they do not include the time dimension. These models are adequate for decisions about the immediate re-optimization of parts of the supply chain, such as decisions on the location of advanced warehouses and distribution centers (Tsiakis et al., 2001). To evaluate a *flexibility configuration,* Graves and Jordan (1995) proposed a single-period production-planning model that minimizes the amount of demand that cannot be handled by the supply chain, the focus being on process flexibility measured by expected sales and capacity utilization for one period.

However, dynamic or multi-period models are appropriate when the consideration of a long planning horizon, divided into several equal periods, is required. For example, when there are decisions on the timing of an investment, dynamic or multi-period models are appropriate. Goetchalckx et al. (2002) developed an efficient decomposition algorithm for multi-period production–distribution networks that considers a market with seasonal demand. Fleischmann et al. (2006) used a multi-period model to develop a strategic-planning model for the optimization of BMW's allocation of various products in worldwide production locations, minimizing the total cost, and taking into account the investment needs in a 12 years planning horizon. Bihlmaier et al. (2009) resorted to a multi-period model to represent and optimize strategic and tactical production planning in the automotive industry.

The option to use one single period or several time periods clearly depends on the specific purpose of each model. In Table 5 we can find some of the more relevant papers we have analyzed, according to the type of model used.

Table 5: Classification of works based on the number of time periods

Characteristics	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Multi-Period Model (Dynamic)	X	X		X					X		X	X		X
Single-Period Model (Static)			X		X		X			X	X			

(1) Fleischman, Feber, Henrich; 2006 (2) Kauder, Meyer; 2009 (3) Santoso, Ahmed, Goetshalckx, Shapiro; 2003 (4) Alonso-Ayuso, Escudero, Garín, Ortuno, Pérez; 2003 (5) Vidal, Goetschalckx;2001 (6) Vidal, Goetschalckx; 1997 (7) Perez, Alvarez, Alba; 2005 (8) Mak, Morton, Wood; 1999 (9) Dogan, Goetschalckx; 1999 (10) Yu, Li; 2000 (11) Klibi, Martel, Guitouni; 2010 (12) Singh, Philpott, Wood; 2009 (13) Goetschalck, Vidal, Dogan; 2002 (14) Bihlmaier, Koberstein, Obst; 2009.

3.2. Decision variables, performance measures, and constraints

Decision variables are, in fact, those variables that one can control in a model, and they should reflect the alternatives for decision-making at the different levels of the planning process. The variables that are more often referred in the literature are related with:

- *Production:* quantity, allocation, configuration, Bill-Of-Materials, (Fleischman et al. 2006; Kuader et al. 2009; Alonso-Ayuso et al. 2003; Vidal et al. 2001; Dogan et al. 1999; Yu and Li 2000; Arntzer et al. 1995; Cohen et al. 1989; Bihlmaier et al. 2009);

- *Investment:* on capacity expansion, on facilities (Fleischman et al. 2006; Kuader et al. 2009; Santoso et al. 2005; Dogan et al. 1999);

- *Inventory:* level, allocation, number of products (Alonso-Ayuso et al. 2003; Dogan et al. 1999; Yu and Li 2000);

- *Transportation*: volume, routes, costs, mode (Alonso-Ayuso et al. 2003; Santoso et al. 2005; Vidal et al. 2001; Perez et al. 2005; Dogan et al. 1999);

- *Flexibility:* reserve of capacity production or product units (Fleischman et al. 2006).

Melo et al. (2009), in an very comprehensive literature review, identify "inventory" as being the most frequent decision variable in the literature, in addition to the typical location-allocation decisions, followed by decisions related with production and capacity. This doctoral project focuses on decisions related with:

- the quantity to move between any two entities, and where each product should be produced;

- if we should open new facilities and where these should be located (network design), and
- if we should increase the capacities (plants or warehouses).

The model should also define the connections to be established, which warehouses to use, the quantity of each material required by the different production processes, and how to transport the materials and finished products (which mode). So, it considers several types of decision variables, with a particular focus on the design of the supply chain.

The decision variables of each model are chosen not only to allow the optimization of the supply chain performance, thus determining the efficiency and effectiveness of an existing system, but also to compare competing alternative systems, as well as to design new systems (based on the values of decision variables that yield the required level of performance).

Beamon (1998) identifies two main categories of quantitative performance measures: based on costs (operational costs and investments), and based on customer responsiveness. Qualitative performance measures are also important in some circumstances: this is the case of customer satisfaction, flexibility (capacity to answer to random fluctuations in the demand), as well as information on material flow integration (Beamon 1998).

The nature of the objective function depends obviously on the chosen performance measures. We can identify three main categories for these measures related to:

- *Costs:* minimize total cost (Perez et al. 2005; Dogan and Goetschalckx 1999; Yu and Li 2000); minimize average inventory levels; maximize profit (after taxes) (Alonso-Ayuso et al. 2003; Vidal and Goetschalckx 2001); minimize labor/production/transportation cost; minimize Net Present Value (Fleischman et al. 2006);
- *Customers:* achieve target service level; reduce lead time (Arntzen et al 1995); maximize responsiveness;
- *Flexibility:* maximize available system capacity; maximize ability to react to uncertainty.

Supply chain models can also simultaneously assess more than one objective, possibly through a multi-criteria approach. Arntzen et al. (1995) combined cost minimization with weighted cumulative production and distribution times. Chen and Lee (2003) developed a multi-objective production and distribution-scheduling scheme for a supply chain that aims at maximizing profit for the entire system, at obtaining a fair profit distribution among all members, and at increasing customer service, not disregarding safe inventory levels. In 2004, these authors broadened the original objective function by considering product-prices satisfaction levels and robustness. Some other authors have also combined cost optimization with customer service level.

Another important element in the structure of this kind of models is the way different types of constraints are modeled. This includes fixed production facilities, limits to total investment, stock levels, plant capacities, available space, conservation of flows (products), customer demand satisfaction, capacity of suppliers and machines, bill-of-materials, or customer service level.

Performance measures should cover the different aspects of supply chains, and can be related to suppliers, delivery performance, customer service, inventory and logistics costs. These measures should probably be based on financial performance when related with strategic decisions and based on operational performance when related with day-to-day control. Moreover specific metrics should be associated to the different decision levels: strategic, tactical and operational. To appropriate analyze the different relevant performance aspects we should define both financial and non-financial measures. The more common combination is *cost* with *customer responsiveness* (lead time, stock out probability).

The process of choosing appropriate supply chain performance measures is difficult due to the complexity of these systems. We can identify four main categories: quality, time, flexibility and cost (inventory cost plus operating cost). Single performance measures are in general inadequate because they ignore the interactions between important supply-chain characteristics. They also ignore critical aspects of organizational strategic goals such as resources (efficiency), flexibility (customer service) and outputs (ability to respond to a changing environment).

Supply Chain Performance Measures should be related with:

- *resources*: total cost, distribution cost (transportation, handling), manufacturing cost, inventory, return on investment (ratio of net profit to total assets – ROI);
- *outputs:* number of items produced, time required to produce a particular item or set of items, number of on-time deliveries, customer satisfaction, and product quality.

3.3. Deterministic models

Dogan and Goetschalckx (1999) studied the integrated design of strategic supply chain networks, with a tactical allocation of production-distribution facilities. Their multi-period model determines the configuration of the production-distribution system that minimizes total costs, given a set of potential suppliers, potential manufacturing facilities and distribution centers with multiple possible configurations, and customers demand with seasonal variations. The only customer service constraints considered are the full satisfaction of demand. Customer demand is considered to be deterministic and the impact of safety stocks is ignored. Under these assumptions, the authors developed a

Mixed Integer Program (MIP) formulation and an integrated design methodology based on primal (Benders) decomposition. A packaging company with 12 products and 200 national customers was used as a real life case study. This integrated approach saved the company an additional 2% over the hierarchical approach where optimal strategic and tactical decisions were made sequentially.

Fleischmann et al. (2006) developed a strategic-planning model to optimize BMW's allocation of various products to global production sites over a 12-year planning horizon (multi-period). This deterministic model is an optimization model of the MIP type with binary allocation variables (a certain product is produced in a certain plant) and continuous flow variables (the yearly quantities in supply, production and distribution). The case study for this automotive industry OEM considers 36 products and 6 production sites. Originally the MIP model has 60,000 variables, 145,000 constraints, with a maximum of 2,000 integer variables, but ILOG/CPLEX pre-processing is able to significantly reduce the model size to 5,200 variables, 4,100 constraints and 400 binary variables.

One of the literature models that is closest to our own model, in terms of goals, is presented in Thanh et al. (2008). They developed a deterministic dynamic model for the design and planning of production-distribution systems, to support strategic and tactical decision-making (opening/closing/enlargement of facilities, supplier selection, and flows).

Kauder and Meyr (2009) also addressed the strategic network planning problem for the multinational automotive industry. The focus is on the allocation of products to plants and on the capacity expansion decisions, for a given network with fixed plant locations. The proposed MIP model aims at minimizing the NPV (net present value) of all capital expenditures and operational costs while considering flexibility of a network in terms of allocation of facilities. The original model is deterministic but it also considers some changes in demand, exchange rates and total available capacity, by the definition of seven different scenarios. A first MIP model searches for an overall optimal network structure considering the planning of investments. A second MIP model also considers *flexibility* and it starts with an initial scenario with 12 periods, 6 plants and 16 products. Then 4 scenarios are developed, that consider a gradual increase of demand. And finally 3 other scenarios are defined, with changes in the exchange rates. These scenarios are applied to both MIP models, considering 6 time periods. It seems that the complexity of this problem/model makes an extensive analysis of the various scenarios quite hard. For this reason, no general statements can be made, and to overcome this limitation, the authors proposed the adoption of a local search approach.

Although the topic is not explicitly within the scope of our research, we have also reviewed some literature related with transportation systems, with particular focus to the work of Jayaraman (1998). This author has considered the relationships between inventory management, location of facilities and the determination of transportation policies in a distribution network environment. He has analyzed the interdependence between these three topics, and has developed an integrated model for the design of distribution networks, that represents their interdependence and the tradeoffs between the associated perspectives and concerns. The global objective of this integrated model was to minimize the distribution design costs incurrent by a firm.

3.4.Stochastic models

To deal with uncertainty, Yu and Li (2000) developed a *robust optimization* model for stochastic logistic problems. According to these authors this seems to be a highly promising approach for solving stochastic optimization problems, based on "robust programming" as proposed by Mulvey et al. (1995a) and Mulvey and Ruszczynski (1995b). Unfortunately this approach has a heavy computational burden preventing wider applications in practice. The robust optimization model generates solutions that are progressively less sensitive to the data in the scenario set. This method integrates classical *goal programming* techniques with a scenario-based data set, to assist a manager in wisely solving stochastic logistic problems. The proposed method transforms a robust model into a linear program that requires only half of the scenarios in the original robust programming methods. Two case studies, with logistic management problems, are used to demonstrate the computational efficiency of the proposed approach: one involving a wine company (3 decision variables; 4 scenarios; 14 deterministic constraints; 62 non-negative variables; only one product) and the other with an airline company (number of scenarios between 1 and 12; between 585 and 7,020 constraints; and between 795 and 9,540 variables). In both cases, the demand was considered as an uncertainty parameter and the objective function consists in minimizing the costs. However, this model can only handle linear models and assumes that all coefficients in the objectives and constraints are crisp. It seems that a natural possible direction of further research would be to integrate the robust model with fuzzy set theory under a nonlinear framework. Such a framework would probably be much more useful in practice, for solving stochastic logistic problems.

In 2003, Graves and Willems developed a stochastic approach essentially focusing in the relation between safety stock placement and supply chain configuration. These issues are however outside the scope of this doctoral project. Chen and Lee (2004), developed a stochastic model that focus on the simultaneous optimization of multiple conflict objectives and uncertain product demands and prices, in a typical supply chain network, with multiple products, multiple stages and multiple periods. They have modeled discrete scenarios with given probabilities for different expected outcomes, and the uncertain product prices are described as fuzzy variables. In a first phase, we have tried to explore this research line, but it proved to be unsuitable in view of the kind of decisions and constraints involved in our models.

In 2007 Chen et al. developed an upgrade of this model, by considering the planning of a multi-product, multi-period, and multi-echelon supply chain network consisting of several existing plants at fixed places, some warehouses and distribution centers at undetermined locations, and a number of given customer zones (in a setting that is very near the physical configuration of the network addressed in our research). Market demands have been modeled as a number of discrete scenarios with known probabilities.

The developed model consists in a multi-criteria fuzzy optimization for locating warehouses and distribution centers in a supply chain network (aiming at satisfying several conflicting objectives, such as the minimization of costs and the reduction of the total transportation times). The problem approached by Tsiakis et al. (2001) is identical, but their mixed-integer linear programming optimization is meant to minimize the total annual costs of the network. For handling uncertainty in product demands, these authors have adopted a scenarios planning approach.

Another approach is presented by Alonso-Ayuso et al. (2003) that developed a stochastic programming model and a specific algorithmic approach for solving supply network design problems with a realistic scale. This model determines the production topology, the plant sizes, the product range, the product allocation among plants, and the suppliers for the different raw materials. The goal is to maximize the expected benefit given by the product net profit over the time horizon minus the investment depreciation and operations costs. Product net prices, demand, raw materials and production costs are the uncertainty factors, taken into account in this two stages stochastic 0-1 programming model (considering strategic decisions and tactical decisions). Initially a tight 0-1 deterministic model version was developed. In a second step, a splitting variable mathematical representation via scenarios was proposed for the stochastic version of the model. A two-stage version of a “Branch and Fix Coordination” (BFC) algorithm approach was also proposed and computationally tested. These tests were performed on instances with 6 sites, 3 capacity levels per plant, 12 products (8 subassemblies), 12 raw materials, 24 vendors, 2 markets per product, 10 time periods, and 23 scenarios (combining different levels of demand and different levels of prices for raw materials). The deterministic test case involves around 3,388 constraints, 3,654 continuous variables and 114 binary variables. In a stochastic environment, these dimensions increase to up 88,743 constraints, 82,326 continuous variables and 906 binary variables.

Santoso et al. (2005) developed a stochastic programming model and an algorithmic procedure for solving a large-scale supply chain network design problem under uncertainty. The supply chain decisions consist in determining which processing centers to build and which processing and finishing machines to procure, with the goal of minimizing total investment and expected operation costs (objective function). The developed solution methodology integrates a sampling strategy (Sample Average Approximation) with an accelerated Benders Decomposition algorithm. A computational study was done with two real supply chain networks (one national network, and the other with an international scope, covering 8 countries), showing the computational effectiveness of the method.

In another research direction, Perez et al. (2005) developed a constructive heuristic procedure for finding good starting solutions to the network design problem with uncertainty parameters. The objective is to find a network design that is "good" across all potentially realizable scenarios. Each network element is assigned a finite capacity, a fixed cost and routing costs. As uncertainty parameters, these authors considered demand and routing costs, modeled through scenarios. A GRASP (Greedy Randomized Adaptive Search Procedure) metaheuristic was designed, with computational results of an acceptable quality. A total of 20 instances with 20 nodes, 140 edges (280 arcs), 10 commodities and 10 scenarios were generated, to carry out the computational experiments.

Franca et al. (2010) developed a multi-objective stochastic supply chain model to evaluate tradeoffs between profit and quality of products. They have based their model in the current situation of many companies with outsourcing in countries such as China, justified by apparent significant gains in profits. However in some cases, this seems to lead to serious quality problems that can be critical for the supply chain.

In another direction, Al-e-hashem et al. (2011) developed a new robust multi-objective aggregate production planning model considering the majority of supply chain cost parameters (transportation, inventory holding, shortage, production and labor costs), taking into account aspects related with human resources (e.g., productivity and training), considering the lead time between suppliers, production sites and customers, and assuming demand and cost parameters as uncertainties. The definition of the objective function was influenced by customer satisfaction concerns and the minimization of total losses in supply chain.

Most models view demand uncertainty as the main problem. Dal-Mas et al. (2011) consider another parameter, price uncertainty, in a study addressing an ethanol supply chain. Their research resulted in a dynamic model to optimize economic performance and to minimize the financial risk of investments, by identifying the best network topology. The study shows that, depending on the specific industrial sector and environment, uncertainty parameters may be different and not necessarily be the demand.

As we have done for deterministic models, we have also reviewed the transportation systems literature with stochastic models. Javid and Azad (2009) developed a model to simultaneously optimize location, allocation, capacity, inventory and routing decisions in a stochastic supply chain. The demand of each customer is considered to follow a normal distribution, and each distribution center keeps a certain amount of safety stock. To solve the model, the authors, first developed an exact solution method by casting the problem as a mixed integer convex program, and then they designed a heuristic method based on a hybridization of Tabu Search and Simulated Annealing. The results showed that the proposed heuristic was quite efficient and effective for a broad range of problem sizes.

In the literature we can find many other approaches to deal with network design problems. Among these methods or algorithmic ingredients we should refer simulation techniques, metaheuristics, Genetic Algorithms, or mathematical programing models. Moreover, many authors refer an additional important issue for modeling purposes: the aggregation of customers, demand and suppliers into geographic zones, or raw materials and products into groups (e.g., according to the type of technology). This is a way to simplify the complexity of problems and reduce computational times (Vidal and

Goetschalckx, 1997; Fleischamn et al., 2006; Kauder and Meyer, 2009; Yu and Li, 2010; Al-e-hashem et al., 2011).

From the models in the literature, the one that is possibly closer to ours was developed by Karabakal et al. (2000) for the Volkswagen supply chain of USA. In fact, our model aims at supporting strategic and tactical decision-making, to contribute to the recovery of the automotive industry, and integrates uncertainty and risk management concerns. Karabakal et al. (2000) developed a combination of simulation and discrete optimization models, to address the problem of analyzing a large number of alternatives efficiently. These models take into account inventory policies, demand seasonality and volumes, customer choice patterns and transportation delays. Their models are only meant to evaluate alternative supply-chain designs. The most interesting aspect in these evaluation models is the consideration of stochastic elements, such as customer demand, customer choice and transportation time, but these elements are only considered in the simulation model. The results indicate clear opportunities for savings in the annual transportation costs.

More recently, research work focused on uncertainty and the automotive industry has been developed by Bihlmaier et al. (2009), but their goals differ from ours, in several aspects. The authors developed a multi-period model for the modeling and optimization of strategic and tactical decisions but the focus was on production planning approaches.

A decision tree is a graphic method used to support decision making under uncertainty, thus being useful for stochastic models. These can be used to evaluate supply chain decisions given uncertainty in prices, demand, exchange rates, inflation, and so on.

The first step in setting up a decision tree is to identify the number of time periods (or stages) into the future that will be considered for decision making. We also need to carefully identify the duration of a “period”, which can be a day, a month, or any other time interval. This should possibly be the minimum time interval over which factors affecting supply chain decisions may change by a significant amount. The next step is to identify factors that will affect the “value” of decisions and that are likely to fluctuate over the time periods. These factors are our uncertainty parameters. For each possibility of fluctuation, of each uncertainty parameter, in each period of time, a probability of occurrence must be defined. When decision trees become too complex to be solved in a reasonable amount of time, simulation can be used to perform financial evaluations on supply chain decisions (Chopra et al., 2001). Georgiadis et al. (2011) proposed a stochastic model based on a decision tree approach, developing scenarios for product demand in a dynamic perspective, for a typical location-allocation problem.

3.5. Conclusions

In the literature of the broad domain under analysis, only a few models related to the automotive industry could be found. Most of these models are of a deterministic nature, or focus on uncertainty related with production and demand, thus neglecting uncertainty related with several other factors that are relevant in modern supply chains. In this work we aim at extending those models to explicitly consider uncertainty, and to develop a stochastic approach to global automotive supply chain networks, supporting strategic/tactical decision making. Other characteristics should also be considered in these models to make them closer to reality, namely: multiple periods (to model impacts of changes in the future), multiple objective functions (to tackle the trade-offs between costs and customer service level), international parameters (as legislation), etc.

Some strategic decisions can be episodic. For example, a customer (OEM) is opening a new factory and wants to build a collocated plant to supply that new factory. We need to understand how supplying this new customer site can be best integrated, in time, with his supply network, and how this interacts or conflicts with the conditions of the previous contractual agreements.

In this research project we aim at developing models capable of supporting decision making for annual operations strategy planning, helping understand how the supply chain network might evolve in a long-term horizon, and optimizing the profitability of operations. For this purpose, such models should be able to:

- define different scenarios for the future evolution of supply, demand, transportation, and other critical elements of the supply chain network;
- analyze relevant new investment alternatives (opening or closing factories, increasing or decreasing capacity, opening or closing warehouses);
- simulate and optimize investment decisions in time;
- or perform sensitivity analysis to understand under which conditions different investment alternatives might become more attractive.

Figure somehow summarizes our literature review related with models for supply chain design, and presents some interesting, potential research lines in the area. These lines have been identified along this chapter of the dissertation, and have strongly influenced our work.

New models should incorporate both strategic and tactical decision-making in supply network design. Looking across “strategic decisions”, the focus is on the configuration of networks (type of locations, number and geographic location of facilities) and production (type, product allocation, product selection). Additionally, “tactical decisions” are concerned with inventory types and levels, and transportation modes (distribution and routing). In our work, we want to develop a strategic-tactical model incorporating most of the features from the works presented in Figure 10, and adding uncertainty factors, constraints and features from international operations, taking into account multiple periods, and simultaneously considering multiple objectives.

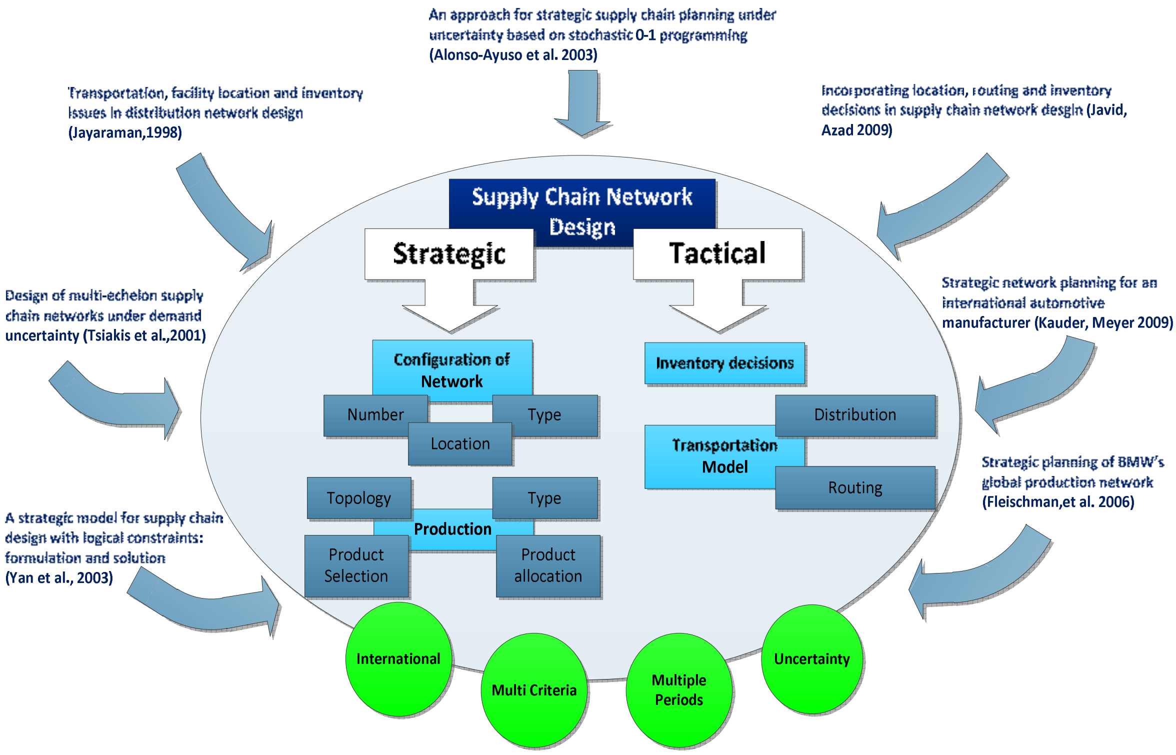


Figure 10: Research positioning

4. Case Study

In order to pursue our research, a strong collaboration with an industrial company in the sector turned out to be fundamental. The nature and scope of this doctoral project clearly required the definition of a sound “case study” to support the definition of requirements, the collection and analysis of data, the design and validation of models, or the discussion and assessment of the results.

As referred in Chapter 1, a supply chain network in the automotive industry (Simoldes Group, in Portugal) was used as a pilot case. With this industrial group we have achieved a clear alignment between our research objectives and their expectations. They are suppliers of the automotive industry, and they work directly with a huge diversity of supply chain members from several countries. Their major customers are OEMs and, since the beginning of the project, they have recognized that some of the major problems they have to face in their own daily operation are problems approached by our research work.

The goal of this partnership was clearly twofold: to guarantee the success of the research project (the PhD thesis) and to respond to the expectations of Simoldes in terms of practical results.

4.1. Case Study

4.1.1. The company

Simoldes is a large, well-known industrial group with headquarters in Oliveira de Azeméis – Portugal. As a part of this group, Simoldes Plasticos is one of the world’s leading developers and suppliers of injected plastic moldings for the automotive industry. It is one of two divisions of the group – the other division, Simoldes Tools, designs and manufactures injection molds.

Figure 11: Simoldes Plastic headquarters

Claimed to be Europe's largest mold maker, Simoldes Group Mold Division supplies plastic injection molds for the automotive industry. They are a group of 7 Production Units and 5 Advanced Customer Service offices, with a sales and marketing structure centered in 4 companies: Simoldes Aços, MDA, IMA and Simoldes Aços Brasil. On the whole, they employ around 950 people.

Simoldes Plastic Division has three factories in Portugal, two in Brazil, one in France and another in Poland. Simoldes Plasticos offers a service to the world's global motor manufacturers.

Founded in 1959, the group began exporting in 1961. Since 1968, Simoldes has been working for the automotive industry, this sector representing the largest component of Simoldes turnover. Simoldes Plastic Division, as referred above, has seven manufacturing companies (units): Simoldes Plásticos, created in 1981; Inplas, in 1993; Plastaze, in 1997; Simoldes Plásticos France, in 1998; Simoldes Plásticos Brasil, in 1996; Simoldes Plásticos Industria, in 1996; and Simoldes Plásticos Polska, in 2003. To support these manufacturing companies, Simoldes Plastic Division has its headquarters in Portugal and two technical / commercial sites in France and Germany (see Figure 12). The main customers are located in Spain, France, Germany, UK and Poland.

Figure 12: Simoldes- location of facilities

Simoldes is, in Portugal, one of the few industrial groups capable of supplying a so large number of main OEMs such as Renault, Volvo, VW, Audi, Nissan, Toyota, Porsche, Honda, Mercedes, GM, Mitsubishi, Bébéconfort and AmtrolAlfa.

4.1.2. Company history

Simoldes was founded in 1959 as a quite small enterprise for the production of molds. This was the beginning of a large industrial group that has been consistently growing along the last decades. The design and manufacturing of molds has always remained a key activity of the group, and currently Simoldes Aços is one of the largest European manufacturers of molds. On the other hand, the plastics injection division of the group (Simoldes Plasticos) is responsible for an important part of the group activity with three factories in Portugal, two in Brazil, one in France, and another in Poland. As referred above, Simoldes Plasticos supplies a large number of OEMs in the automotive sector.

Simoldes industrial group is owned by the family of Mr. António Rodrigues who was one of the starters of the enterprise and is an extraordinary example of self-made-man and entrepreneur.

Simoldes Aços started out in Oliveira de Azeméis, as manufacturer of molds for domestic items and toys. The first strategic change took place in April 1963 when the company moved premises. The expansion of the business was already a strategic company objective.

In 1966, after an in-depth market research carried out at an international level, followed by a wide advertising campaign, the company participated, for the first time, in an international exhibition, in Spain. At this time, the role played by intermediaries was crucial for the company's expansion, and by manufacturing molds for the UK and the United States, doors have been opened for opportunities abroad. In fact, in 1968, Simoldes Aços exported directly for the first time, with the UK being the first country of destination.

At the beginning of the 70s the construction of a new Simoldes Aços building was started and in April 1974 these new premises, where the company is also currently based, were officially inaugurated.

When many companies were in decline because of the political situation at the time, Simoldes gained momentum for the years to come. Through efficient management, excellent facilities, machines and skilled labor, the company was able to better respond to the requirements and needs of the market, and to strengthen its image as a molds manufacturer.

In 1976/1977 an extensive search for new markets started with stands at trade fairs in Chicago, Birmingham and Gothenburg, and with the participation in trade missions to the United States, Canada, Venezuela, Holland, and Denmark. It was during this decade that Simoldes Aços started to manufacture molds for the European automobile industry, more specifically for countries such as France and Sweden. Clients included Volvo, Saab and Renault, although indirectly at the time.

At the beginning of the 80s, partly driven by the setting up of the Renault factory in Portugal, the opportunity arose to expand activity into a new business area: the injection of plastic components. The aim was to supply the end client, directly to their production lines with the needed plastic parts. Simoldes Plasticos was then created, being the first company of what would latter become the Plastics Division of the Simoldes Group.

Figure 13: The logo of Simoldes Plastic Division

At the beginning of the 90s, ten years after the company's great international leap, the group started to diversify with the opening of MDA - Moldes de Azeméis in 1994, a company specialized in advanced technology and the manufacturing of large-scale molds. In 1996, IMA – Indústria de Moldes de Azeméis was founded, and in 1999 a manufacturing unit was opened in Curitiba, Brazil, with the name of Simoldes Aços Brazil.

With the arrival of the new millennium and as part of the ongoing group strategy, new investments were made in the acquisition of new mold manufacturing units, first with IGM – Industria Global de Moldes and later through the acquisition of MECAMOLDE – Moldes para Plásticos and UL Moldes, both in Oliveira de Azeméis.

With a young and dynamic team of collaborators, the molds division of the Simoldes group produces and exports to more than 30 countries, including France, Germany, Spain, Sweden, Belgium, the United Kingdom, Switzerland, Iran and Turkey.

The company aims now at becoming more and more an integrated service provider, without forgetting the specific characteristics of the different markets and the principles of total quality and full compliance with deadlines. To meet today's market needs requires a constant effort to increase productivity, in order to guarantee high levels of competitiveness.

The Simoldes Group currently supplies some of the largest companies in the automobile industry, including Renault, Volvo, Saab, GM, Ford, Peugeot, Mercedes, Citroen, VW, BMW, and Seat.

Figure 14: Main products and customers

These clients are mostly multinational companies (OEMs) with manufacturing facilities on several continents, and in many cases centralizing purchases in their country of origin. However, they purchase components and materials on an individual basis, while sharing information and common purchasing policies.

Simoldes is now aiming to become a global partner within the automobile industry. The need therefore arises to add companies to the group that specialize in smaller molds, so as to provide more and more integrated solutions.

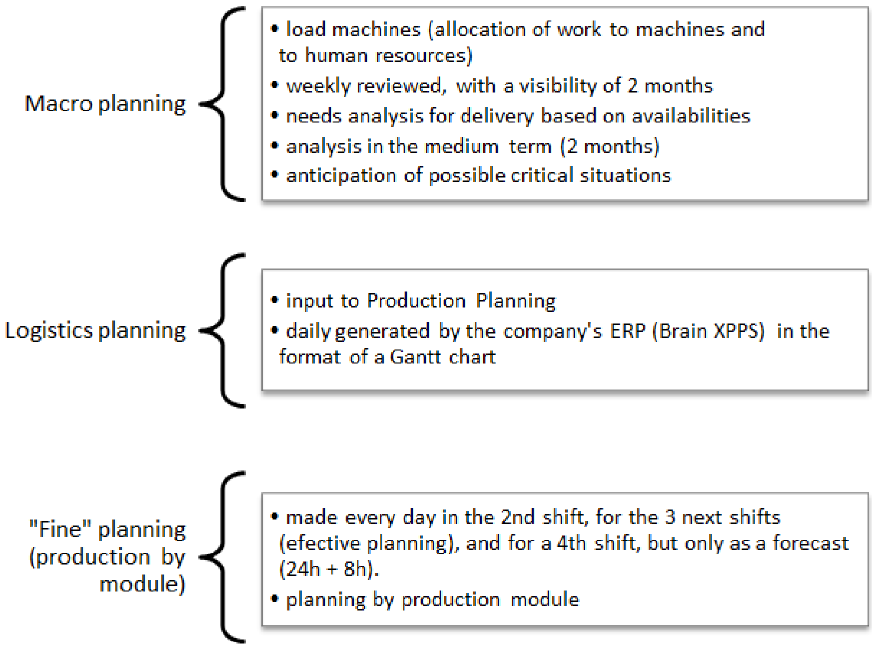
4.2. Operations Management

4.2.1. Production Planning

Simoldes operates 8 hours per shift, 3 shifts per day, 5 days per week. Weekends provide a certain production flexibility, used to increase the production volume or to overcome any loss of production capacity during the normal operation period.

Every week each production unit develops a production plan, taking into account human resources (through the analysis of a Gantt chart), and labor availability (based e.g., on the absence of operators). This analysis often leads to restructuring of the work plan, considering that this is a critical factor (and resources are limited). Production planning pays a lot of attention to these limitations, taking into account factors such as the Setup Time constraints and the information sent by customers (via EDI) with 2 weeks of a "frozen" plan, and 3 months of forecast. The "frozen" plan allows production planning and the "explosion" of the MRP (Material Requirement Planning). The forecast component allows planning stocks and resources (machines, people).

The planning process includes 3 phases as showed in the following diagram.



4.2.2. Processes

As part of this doctoral project, the author spent some months closely working with several people in the company. During this internship, a lot of quite heterogeneous information has been collected and analyzed. Data and information have been gathered by multiple interviews, observation and data collection, allowing the development of a comprehensive global scheme (“map”), with the main steps of the global industrial process (see Figure 15). We could then analyze in detail, the production and logistic flows. This work was fundamental to understand some details and features of the daily operations.

In this map we can observe the production and logistics flows in the Simoldes plants, as well as all type of decisions taken during these processes. The lead times between the company, the suppliers and the customers, are also represented in this diagram (forecasts/orders).

The whole process starts when the planning department receives information from customers, with fixed orders for the next 8 days, and forecast orders for the following 180 days (used to reserve capacity and support the planning process). With this information planning is performed, and information is sent to suppliers (orders of raw materials and lead times), to production (production plan) and to the logistic department (stocks, transportation and delivers).

The production process starts with a “mix or not?” decision related with the color of the final product: black does not require any mix of materials; any other desired color requires mixing different colors of the same raw material. When the first step (preparation of the raw-materials) is over, the injection of final products can start. Then, the products are put into internal containers and go to the Packaging department. Here, two situations can occur: either the product is finished (being assigned the final code type 1); or the product requires assembling, painting or some outsourced operation (code type 2). Products with code type 2 return to production before leaving the production process. Finally, the product can be inspected if required. Products with defects can be classified as “scrap” (no rework is possible, and they will be converted again in raw materials), or they can be reworked. Products that are OK, i.e., that have the right quality level, are ready to be sent to the client.

Then the quality department releases the products to the logistics department that will prepare cargo and shipping (deciding about the transportation mode, the carrier and the schedule).

As referred above, the “map” in Figure 15 resulted from an interesting collaboration with Simoldes, and it formed an important component of the subsequent research. Moreover, in itself, this scheme helped the company to structure and understand their main industrial / logistic processes (showing the flows, steps and lead times in only one scheme).

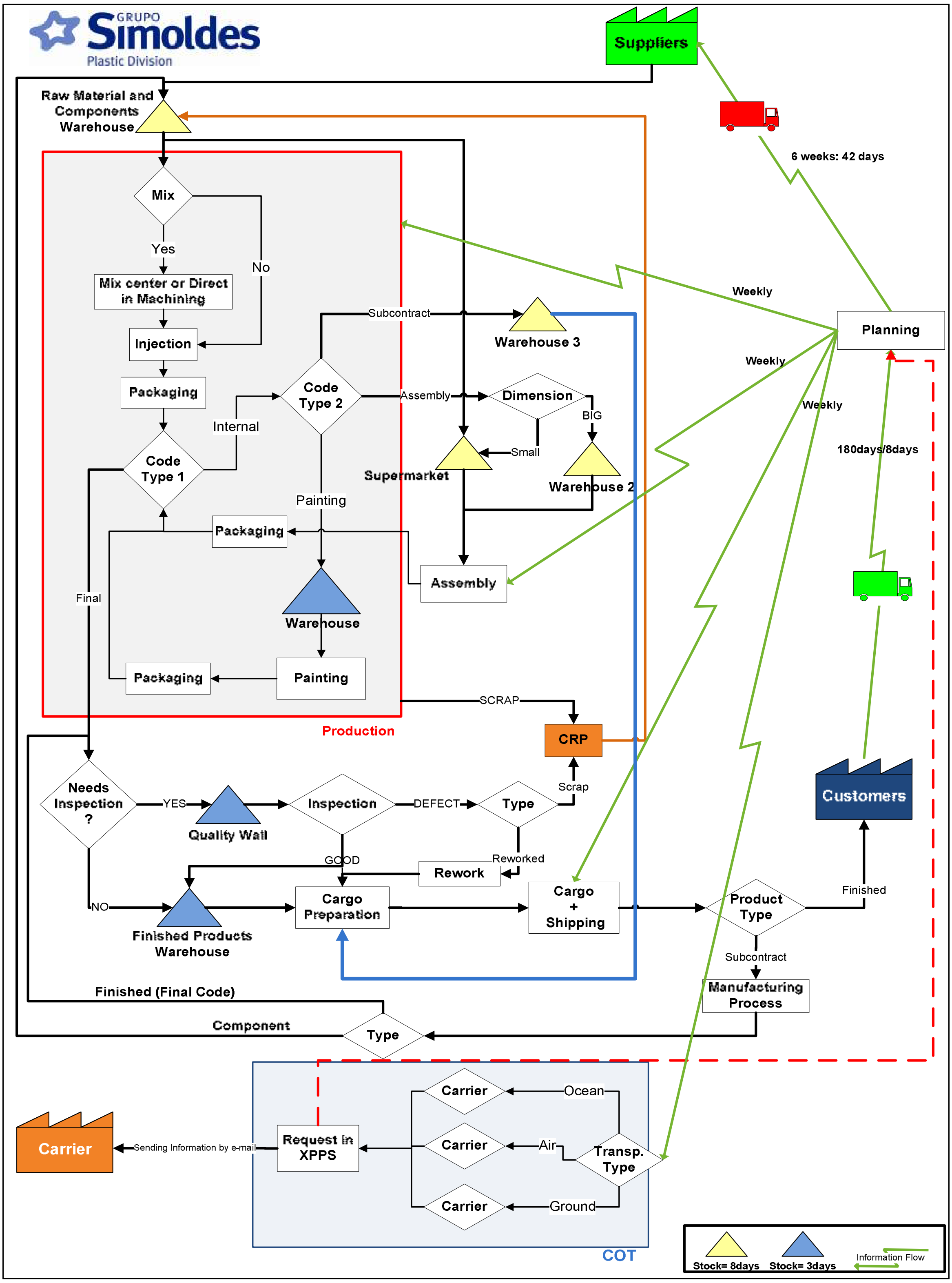


Figure 15: Simoldes Process

4.2.3. Customer agreements

One main component of the whole system operation is related to the process of establishing new agreements with customers. Currently Simoldes, like many major companies in the automotive sector, has a rather rigid process to develop such agreements.

When the customer sends Simoldes the "project of a new product" and all characteristics of the product to be manufactured, a technical team analyzes the production requirements and processes, and defines two prices: an APrice (production plus transportation) and a BPrice (production alone). The customer then decides if he wants to be responsible for the transportation (logistic) costs, or if he is willing to pay more to receive the product in his own facilities. During the definition of this agreement, discussions have to take place about the lot sizes, packages, project life cycle – from SOP (start of project) to EOP (end of project) – and average production quantities per year. At this stage, a commitment is taken by the customer to deliver regular demand forecasts to support production planning.

Another important issue is related with the selection and choice of suppliers, that can partially be imposed by the customers or by Simoldes. All customers are forced to guarantee some quality and security levels (as imposed by the European Union), and this is the reason why we do not include in our research the possibility of changing suppliers, once a production project has been launched.

Sometimes, the customer decides which specific plant should produce a given product (he might, for example, want the nearest plant instead of the cheapest). Otherwise Simoldes analyzes the available production capacities, the production and logistic costs, the available logistic resources (e.g., warehouses) and decides about the allocation of each product to manufacturing units.

After some "brainstorming" with the company we have defined two research generic themes considered to be relevant for both parts. These themes should be related to decision making and planning at strategic and tactical levels.

Concerning the strategic level, it should be noted that some strategic decisions can be episodic. For example, a customer (OEM) is opening a new factory and wants us to build a collocated plant to supply that new factory. We need to understand how supplying this new customer site can best be integrated, in time, with his supply network, and how this interacts or conflicts with the conditions of our previous contractual agreements.

Another research goal is to provide support to decision making for a yearly operations strategy planning, for helping understand how the supply chain network might evolve in a long-term horizon, and for optimizing the profitability of operations.

The scheme in Figure 16 has been developed to briefly describe all steps in the “strategic decision process” taking place from the first contacts with the customer to production start.

4.2.4. Representative Decision Process

As previously mentioned the company has confronted us with two different scenarios, which can be critical in terms of decision-making processes. The most frequent scenario involves all the decisions the company has to make when establishing a new production contract, i.e., when the group wins a new project. Here this scenario is called a "New Project".

The first step in this scenario is to decide about where to locate production. The normal, logic decision seems to be choosing the plant that is closest to the client. However, this option is not always the most advantageous in economic terms. For example, a customer in northern Germany is closer to the factory in France but production costs are much higher than in Poland. Therefore, we need to assess the logistics and production costs in an integrated way, to be able to choose locations.

After choosing the production site, the next step is to assess the available production capacity. This evaluation takes into account the type of machinery required for production, checking for example whether the number of machines that are able to work with the molds of the project is sufficient for the production under analysis.

The molding machines are classified according to their tonnage, i.e., the pressure that the machine can put into the mold. The pressure required differs from product to product. The company currently has seven "machine ranges" (measured in terms of tons): 80-130; 350-450; 500-650; 700-900; 1000-1200; 1300-1600; and 1800-3200. A mold that requires a pressure of 800 ton can be placed in machines with higher capacity. However, the energy costs are higher than those of the “right” machine (700-900), and consequently production costs increase.

After choosing the plant, if this does not have the required available capacity, two alternative options have to be evaluated:

- to increase the production capacity by buying new equipment for the additional production or, if possible, to increase the number of shifts;
- or to move the project to another plant.

Again, in economic terms, the evaluation is based on a comparison of the required investment and the costs to produce in another plant.

After deciding where to produce logistics decisions have to be taken: after being manufactured, products are either sent directly to the customers, or they are temporarily placed in storage. This last option is sometimes required by the customer contract. Most customers work in a Just-In-Time philosophy, thus requiring the proximity of suppliers for the sake of flexibility (the closer the supplier is, the easier it is to respond in short times). When plants are far from the client, one could opt by deploying an advanced warehouse. This would be an indirect way to satisfy the closeness requirement.

Concerning warehouses, the question is now about their precise “locations” and sizes. Currently Simoldes has several advanced warehouses: some are owned by the group, and others are subcontracted.

If the required warehouse does not exist or if it does not have the required capacity, it is necessary to decide whether it is more economically advantageous to acquire a new facility, or to lease or rent it.

If the option is to purchase it, the next decision is related with its dimensions, taking into account not only the current needs, but also the business potential in that geographical zone (as potential customers may represent new contracts).

If the warehouse is outsourced, the company should make an assessment of the several alternatives, to check which is the most advantageous (in terms of costs, responsiveness, scale, logistics infrastructure).

The second scenario under analysis refers to an increase or decrease in product quantities of an existing project– here this scenario will be called "Change." In this case the process is identical except in what concerns the first decision - where to produce? - since the project is already allocated to a company (plant).

Somehow we might say that, in terms of strategic / tactic decisions, the main concerns of the company are related to these two scenarios, and involve deciding where to produce and how to manage the stock, based on a complex economic evaluation of the different alternatives.

Figure 16 summarizes the decision processes described above.

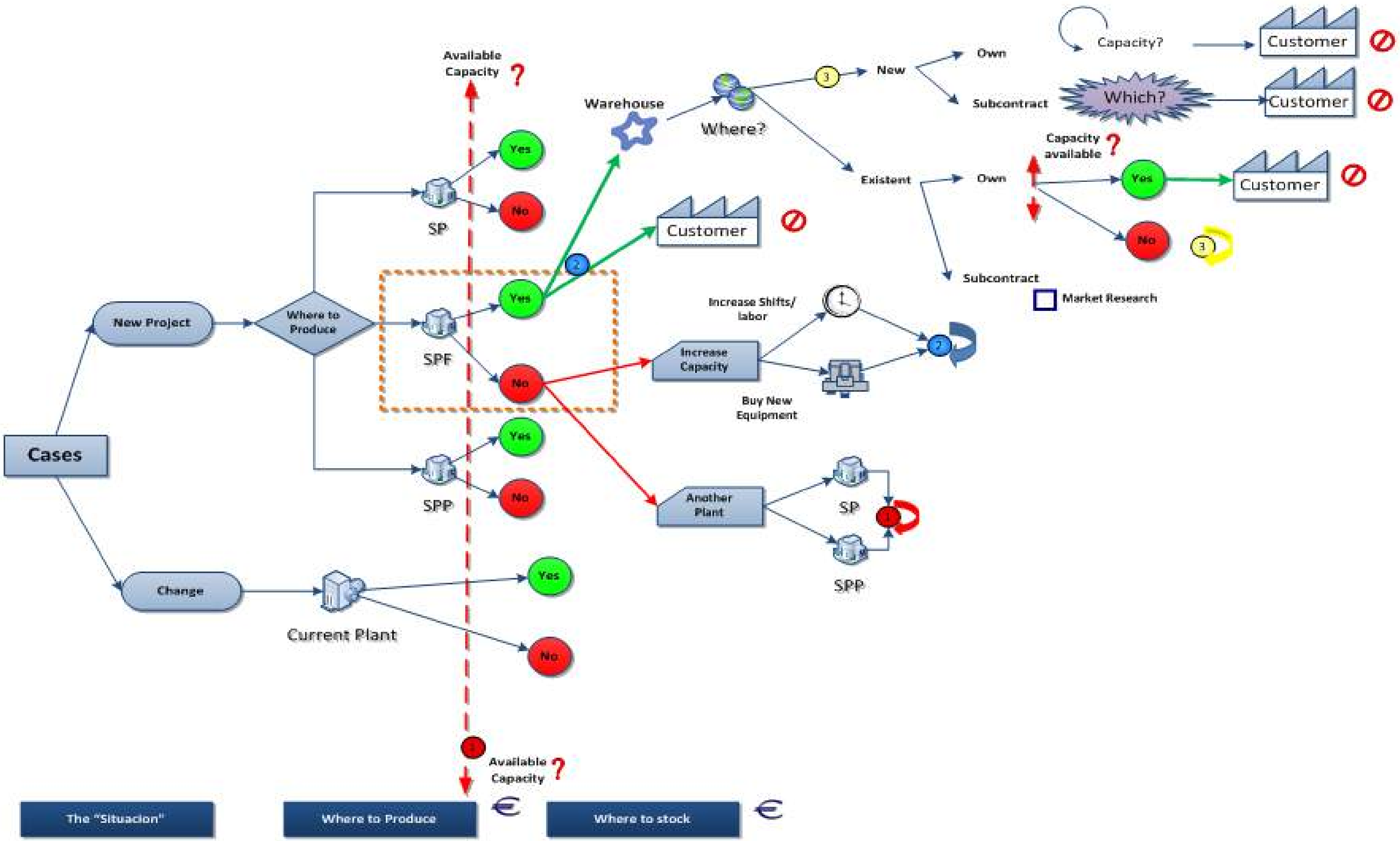


Figure 16: Strategic Decision Process

4.3. Data Collection and Visualization

To help developing the described research and to feed and develop our models, a fundamental step consisted in collecting different types of data and information from various sources. Some of this data was collected in the case study but more general data required a search in the literature and in the internet, and a considerable pre-processing.

Among other aspects, this process involved three main concerns:

1. a detailed description of the Supply Chain;
2. the identification of potential Business Zones;
3. the characteristics of potential Business Zones (taxes, legislation, policies, etc.).

The first contacts with the company have been used to identify their expectations, to define the scope of the collaboration, and to guarantee the alignment of the case study with our research goals. Moreover with a comprehensive literature survey, we have identified the main existing gaps and the theoretical foundations to support the development of our models. The case study provided us with the data, and with a practical knowledge about the automotive supply chain (this being complemented by the state-of-the-art) and enabled us to be closer to the industrial reality.

To facilitate this process we have done an internship at Simoldes during 12 months. This experience allowed us to understand the issues involved in tactical and strategic decision-making, and also to know the main operational characteristics of the sector. Our activity has been structured in two phases:

1st phase: Collection of general information and understanding how the company operates - interviews were conducted with the people responsible in the different areas relevant for our work.

2nd phase: Gathering information about the location of facilities (production units, warehouses, and customer support centers), suppliers and customers, having as main goal to develop a scheme/map of Simoldes' supply chain – additionally data was collected on the yearly business volumes concerning physical movements to customers and from suppliers (quantities in m^3).

With the collected data, we were able to draw a map of locations, which represents those geographic zones that have a higher concentration of entities (suppliers and / or customers).

The identification of "potential business zones" was based on the geographic distribution of OEMs, i.e., the customers in the case study. Then a careful analysis was done on the importance of customers, taking into account the business volume (as published by each company every semester) and the type of relationships already existing with Simoldes (as it is obviously easier to get new contracts from companies that are familiar).

Finally, we have done a summary with the main characteristics of each potential business zone. For this purpose, the information we have considered included: labor costs, transportation costs (based on the fuel cost) and a ranking expressing the easiness of doing business, based on several factors (starting business, dealing with licenses, registration property, getting credit, protecting inventors, paying taxes, trading across borders, enforcing contracts, closing a business).

The collected data were represented in the form of maps as a way to visualize the characteristics of each geographical area, for example, the concentration of current business (customers and suppliers). This analysis can be made much easier, by using the map showing the geographical location or the map showing the concentration (m3) of transported products.

The company recognized that the full representation of their entire supply chain is an interesting tool for supporting decision-making (figure 17). This representation allows a global view of the company presence in the world.

The map on figure 18 allowed the company to visually recognize the spots with high business concentration. This analysis also led to the identification of infrastructure gaps along some "clusters".

Figure 19 shows the potential clients in areas where the company already has some facilities, therefore identifying new opportunities to explore those facilities. This map has been developed after we have recognized the difficulty in assessing the economic viability of some potential investments, and it shows the more relevant production and transportation costs.

The above two maps have been placed “side by side” and have become an important tool to support decision-making. This seems to be a good way to facilitate information crossing about the various locations, and can be used to implicitly assess the potential of new sites.

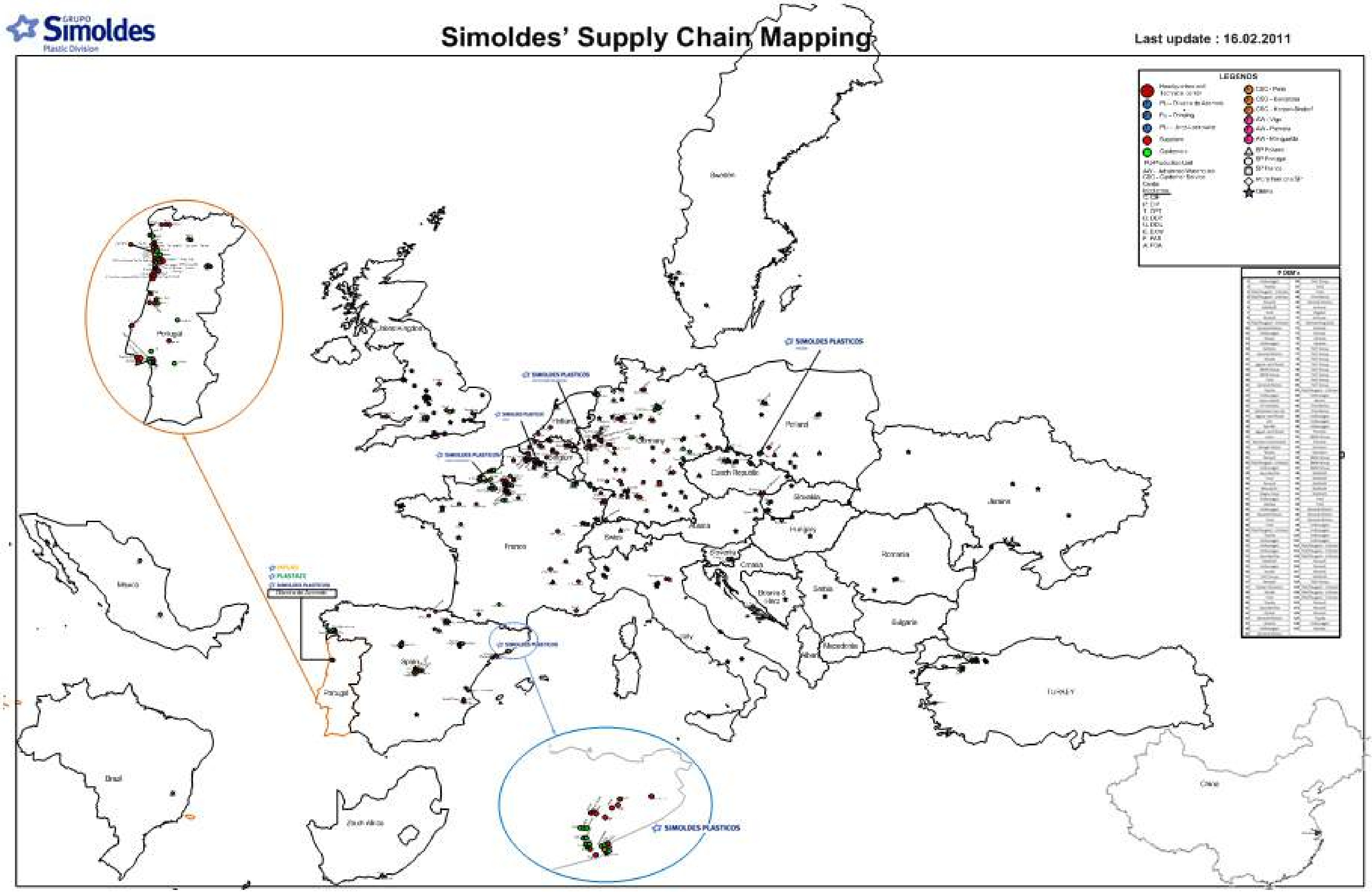


Figure 17: Simoldes' Supply Chain Mapping

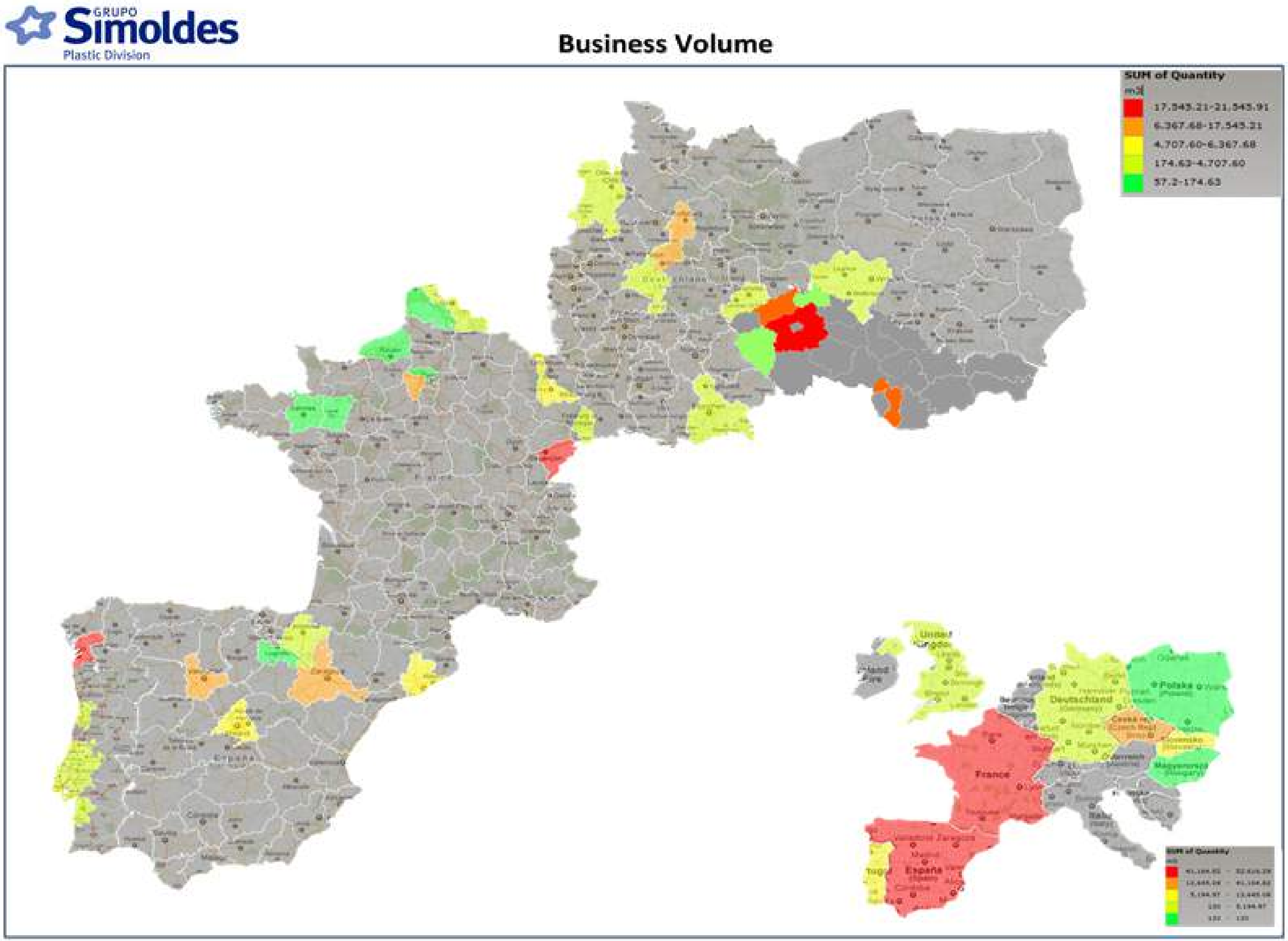


Figure 18: Business Volume

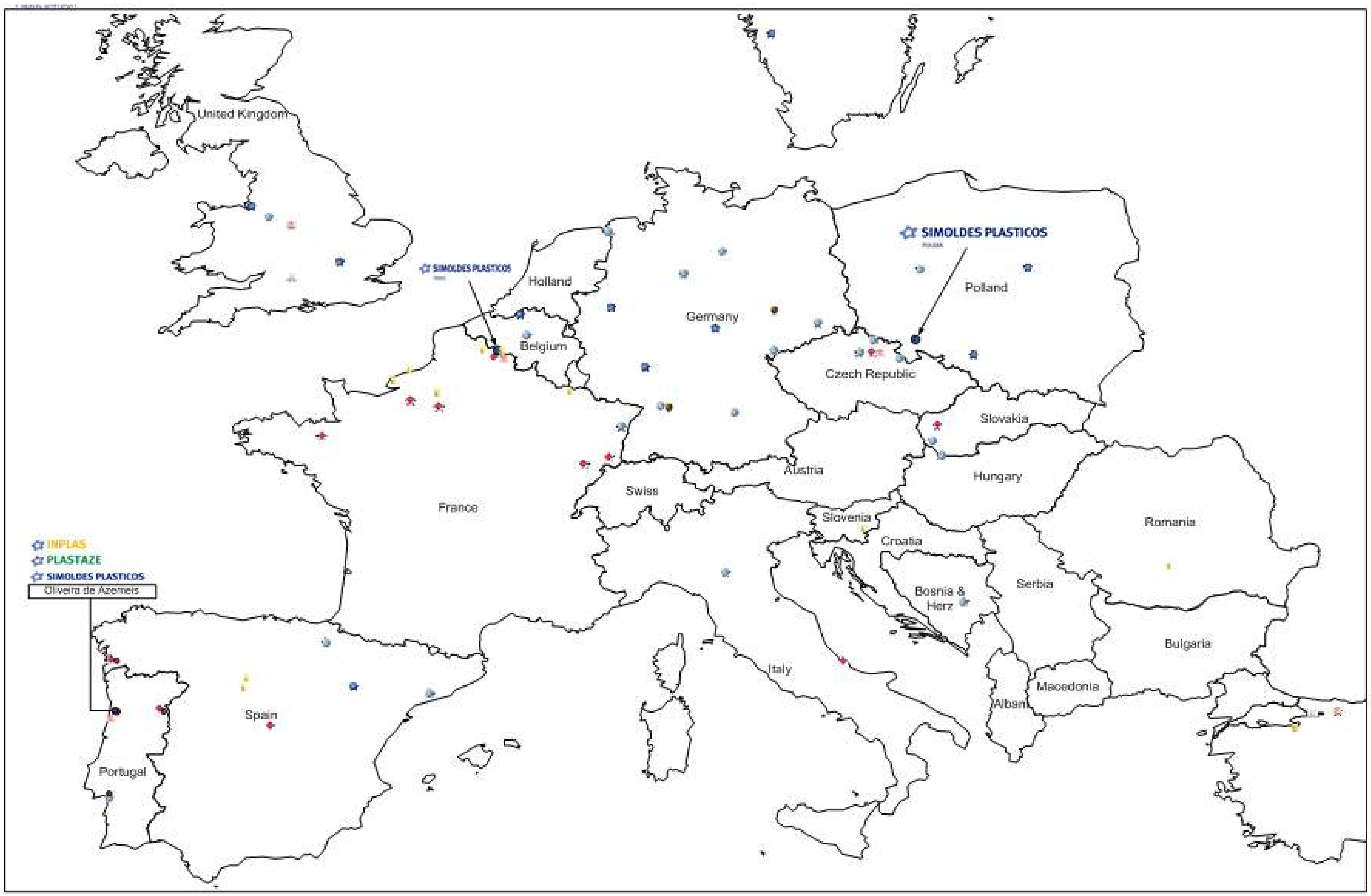


Figure 19: OEM'S mapping

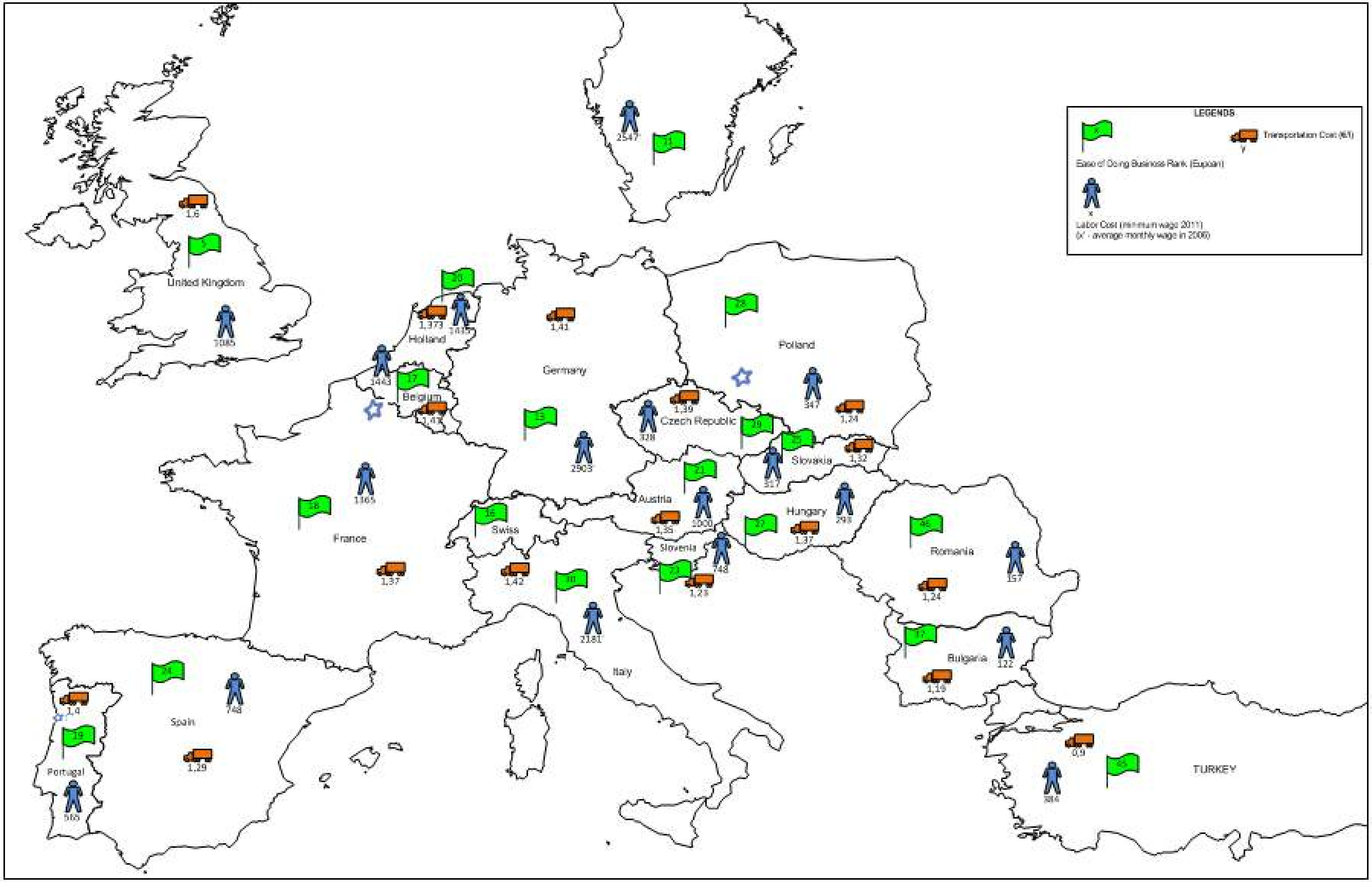


Figure 20: Classification by country

4.4. Data processing and validation

As referred above, in the development of this project, and particularly during our internship at Simoldes, we have pursued some research activities contributing for the achievement of the dissertation goals, but always trying to deliver interesting results for the company. In this section we present some of these results. This report is very concise due to restrictions on the disclosure of information.

In a first step we have developed a map of the global production / logistics processes (from the customer order to product delivery). We have then focused our attention in logistics, collecting as much data as possible in this area.

Several maps have been developed (see figures 17, 18, 19, and 20), with the locations of facilities around the world, with the distribution of all major OEMs in European countries (along with the forecast of production volumes of each car model produced by the OEMs), with all relevant data for taking strategic decisions. Several combinations and forms of organizing these data resulted in several other maps, considered to be quite useful for supporting the analysis of concrete cases, relevant for the company's strategy.

The internal data from the company was also represented and studied in a graphical way. In figure 21, an example of these maps is presented (with synthetic, not real data, due to confidential issues).

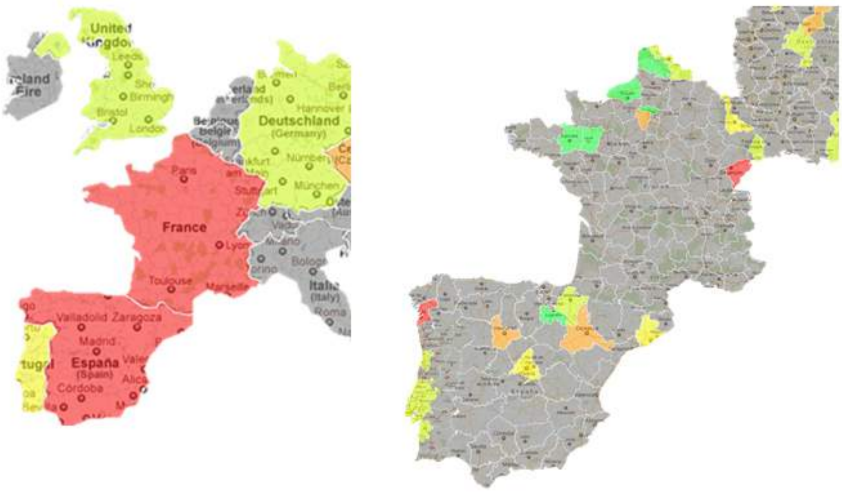


Figure 21: Example of maps used to study the current situation

These types of maps allowed us to better understand the current distribution of the business volume. Such maps, along with some auxiliary data, have been used by the company to discuss a set of relevant issues, and to produce short-term recommendations.

These tools could in fact be used to structure and assess situations such as opening a new warehouse in a specific place and change some flows of materials, reducing costs.

The analysis developed started by a macro perspective focusing attention on countries, viewed as objects of analysis. Later, in more restricted geographical areas and in some specific cases, regions and cities have been analyzed, in order to test the feasibility of including new infrastructures in the existing network.

For confidentiality reasons, we cannot present these studies or the obtained results.

5. A model to deal with uncertainty in supply chain design

The literature review presented in in the first chapters of this dissertation has revealed a clear opportunity for research related to the development of a stochastic model for the automotive supply chain network, designed to help and support organizations in taking strategic-tactical decisions. Moreover our work has been structured with a clear concern of matching scientific research with industrial relevant results. For that purpose we have established a partnership with an industrial company in the sector, which has provided us with data and guidelines, and has helped us to identify the main requirements of a basic model, as well as its structure. Therefore by comparing and combining the industrial and literature inputs, we have been able to define the main features to be considered in this model.

The model is intended to support decision-making for network design (configuration of the network, product allocation), investments (capacity or new facilities/links) and transportation. Moreover, as previously mentioned, we want to develop a stochastic model, and therefore we need to identify and tackle the main uncertainty factors present in this industrial sector.

Observing and studying the daily operation of the pilot company, as well as their procedures for strategic and tactical decision-making, we have identified inflation as the current main uncertainty, in terms of market sustainability. Oil price is also uncertain, but in general, when it goes up, it influences all different actors and factors (e.g., raw materials and transportation costs) in a similar way. So, if a country is currently competitive because it offers a low price for transportation and raw materials, we expect it to remain competitive, in a similar way, in the future. Another interesting uncertainty factor is related to the exchange rates, due to the globalization of automotive companies and the fact that several countries and their currencies need to be considered. Nevertheless, in our case study the impact of this factor is rather low due to a Euro based normalization during the contract placement.

Finally, we often need to consider the energy price (mostly electricity) as one uncertainty factor having a strong impact in practice. Nowadays, with the electricity production sector being restructured following the liberalization of some national markets (e.g., Spain), new sources of electricity generation (e.g., solar, wind) are becoming more and more important. In this context, incentives to own generation and tax policies also play an important role.

Taking into account the case study requirements, we have investigated the impact of inflation as an uncertainty factor. Inflation consists in an increase of the general level of prices of goods and services in an economy. Comparing data published by the Statistical Office of the European Union (Eurostat), we can notice that consumer price indices rose only at a moderate pace during the last two decades. During the 1990s inflation decreased, but after 1999 it started to increase again. The pace of price increases was at around 2 % per year until 2007. In 2008, when the global economic and financial crisis started, the European Union had a new record, with an annual average inflation rate of 3.7%. In 2009, the annual inflation for the EU was 1.0%. In 2010 the inflation rate reached previous levels becoming 2.1%, but in 2011 it increased 2.72% on average. In February 2012 its value was 2.7%.

However, in this work we are basically concerned with the possible different values and evolution of the inflation rate, for different zones in Europe (e.g., Eastern Europe, Central Europe, and Iberian Peninsula) and not for the European Union as a whole.

It should be noted that the use of inflation in this research is a first way to assess and validate a model that will be extended to simultaneously deal with other uncertainty factors.

5.1. Approach description

At this stage of the research we have used some simplified problem instances directly inspired by a first version of the case study, as described next.

Let us assume a company has a typical supply chain with suppliers (r), customers (c), advanced warehouses (w), plants (with warehousing and production units) (l), potential locations for opening new advanced warehouses (h), finished products (p) and raw-materials (m). Figure 22 schematically represents the type of connections established between all members of this supply chain.

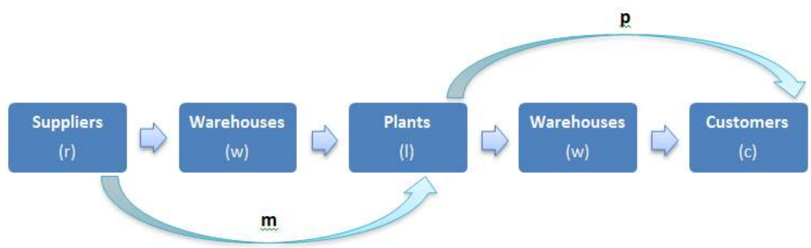


Figure 22: Example of a supply chain network

Suppliers (r) are companies that can send raw materials and components to warehouses or directly to the plants. Warehouses (w) are all storage units that are not located at the production units (plants), so they can be advanced warehouses or distribution centers. These entities can receive materials (m) from suppliers and send finished products (p) to customers. For this reason they are “duplicated” in the supply chain scheme of Figure 22. Warehouses are always linked to plants (they send raw materials/components and they receive finished products). Plants (l) are all production units (they convert raw materials/components into finished products) in the supply chain. In the plants we also find (internal) warehouses for raw materials and finished products.

Customers (c) are naturally the last entities in the supply chain. They receive finished products from plants and/or warehouses. Materials (m) are raw materials, components, or sub-components used in the production process of finished products. Products (p) are finished products to be sent to customers.

The potential locations (h) are “suggestions” for new locations of facilities, that are possibly going to be integrated in the current supply chain. A new location can be used for a distribution center/warehouse closer to the customers and/or suppliers. According to the company’s strategy, these new warehouses can be acquired, leased or “subcontracted”.

Trying to minimize the total costs for operating the supply chain, the model should be able to decide about the quantity to move between any two entities, where each product should be produced, if we should open new facilities and where these facilities should be located (network design). The model should also define the connections to be established, which warehouses to use, the quantity of each material required by the different production processes, and how to transport the materials and finished products (transportation mode).

In order to explicitly consider uncertainty, the model is characterized by two decision stages (thus being a dynamic model). In an illustrative example (defined below), we will consider several possible scenarios (s) taking into account different inflation rate evolutions in the two considered periods. Each scenario (s) involves two events (e), one per each time interval or period (t) between the stages. An event is an evolution of the uncertainty factors being studied – in this case, only the “inflation rate” is considered. Each event has associated a probability of occurrence Pb_e.

As referred, we have structured the model around two decision stages, with uncertainty modeled over scenarios s with a specific probability of occurrence associated.

For illustration purposes, we will consider an example where a scenario s (s=1,2,…) is a path in a scenario tree, with a set of nodes, one in each instant of time. We will also consider periods t (t=0,1,..,T) that are intervals of time between two instants.

In the 1st stage we will take Structural Decisions related with the definition of a physical configuration for the supply chain, based on previously known data. In the 2nd stage we will make Contingent Decisions taking into account the behavior of the system during the first time period, and the values of the uncertainty factor.

In this work, the paradigm chosen to deal with uncertainty was the “scenario tree”, with conditional probabilities associated to each scenario, i.e., the probability of each branch depends on what has happened in the previous periods.

If we consider 3 instants and 2 time periods (t1- between instants 0 and 1; t2 - between instants 1 and 2), and 3 different uncertainty behaviors (one per branch), we will have 9 different scenarios as shown in Figure 23.

So, in instant 0 we will take decisions about the network configuration and flows of goods for time period t1. In instant 1 we will decide again based on the value of the uncertainty factor, but only about flows, thus assuming the network configuration is very complex and expensive to be changed.

Each node represents an event e (resulting from the evolution of the uncertainty factor in a specific period) and it has associated a probability of occurrence Pb_e.

$$\mathrm{e} \in \mathrm{E} = \mathrm{events} \qquad\qquad \mathrm{e} = 0,1,2,\dots$$

We also denote a(e) as an antecedent node of event e, and t(e) as the time instant of event e. To simplify our notation we define subsets of events:

$$E_{t'} = \{e \in E: t(e) \leq t'\}$$

So, a probability distribution for the inflation (the uncertainty factor considered here) is specified for the geographic location of each customer. The model gives us the location of facilities to open, the capacities required to satisfy the demand, which facilities should we use, and the quantities that should be moved between any two entities. These decisions aim at minimizing the expected costs, considering transportation, warehousing, production and new investments in capacity.

We consider here a discretized planning horizon (in the case study, the horizon is divided into semesters).

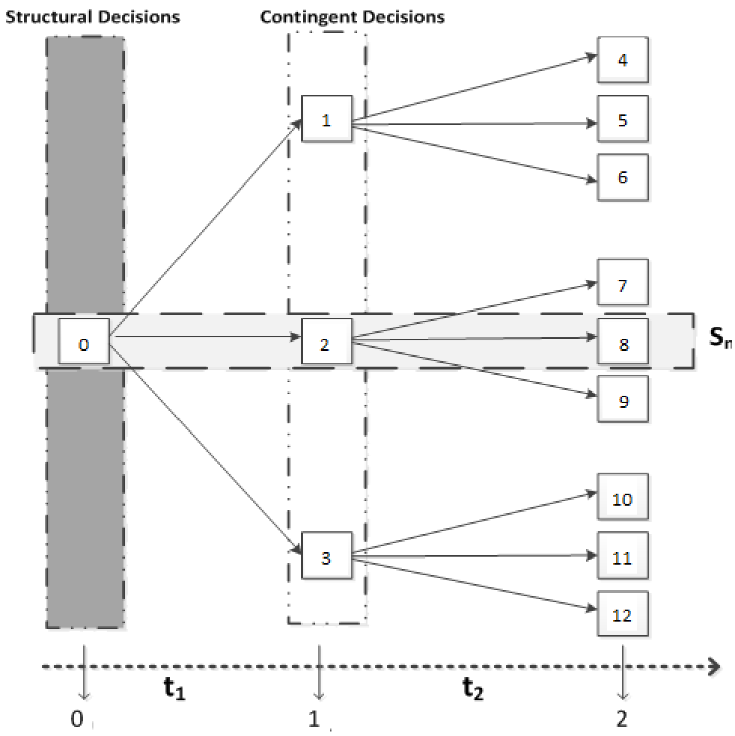


Figure 23: Scenario Tree

5.2. Mathematical formulation 1

5.2.1. Indices

As referred above, the supply chain network is defined as a set of entities (nodes) and a set of arcs that establish connections between pairs of entities, and that represent the flows of products across the supply chain.

$r \in R =$ suppliers	$r = 1,2,3, \ldots.$
$c \in C =$ customers	$c = 1,2,3, \ldots.$
$w \in W =$ warehouses	$w = 1,2,3, \ldots$
$l \in L =$ plants	$l = 1,2,3, \ldots.$
$h \in H =$ potential new locations for warehouses	$h = 1,2,3, \ldots.$

In our models, suppliers and customers can be represented (viewed) as individual entities or as clusters/groups of entities, as a way to reduce the problem dimension.

The potential locations (h) are “suggestions” for new locations to be included in the current supply chain. A new location could be a distribution center /warehouse closer to the customers and/or suppliers. According to the company’s strategy, these new warehouses can be acquired, leased or “subcontracted”.

To simplify the notation, we will in general assume that flows occur between an origin i and a destination j (these may represent homogeneous geographic zones, rather than specific locations).

$$i \in I = \{R \cup W \cup L \cup H\}$$

$$j \in J = \{W \cup L \cup H \cup C\}$$

We will also consider parameters related to the bill-of-materials, namely the type of materials (m) required to produce the final products (p). Each type of finished product requires the same types of resources.

$$m \in M = \text{types of materials for production} \qquad m = 1,2,3,..$$

$$p \in P = \text{types of finished products} \qquad p = 1,2,3 \ldots$$

These will also be grouped into a set K to simplify the notation in some parts of the model.

$$k \in K = M \cup P$$

Concerning transportation, each type of vehicle is associated to a different cost per usage (tariff) depending on the dimensions, mode and route (origin and destination). The set V represents all types of vehicles considered in this model.

$$v \in V = \text{vehicle types} \qquad v = 1, 2, \ldots$$

5.2.2. Parameters

ir_{ei}

$= \text{expected increase in annual inflation rate in the geographic zone of entity i under event e}$

$Pb_e = $ probability of occurrence of event e

$d_{ij} = $ distance between entities i and j

$cb_h = $ business potential of location h (scale 1 to 5)

$df_{cpt} = $ demand for customer c of product p (in m^3) in time period that begins in instant t

$cl_h = $ labor cost in location h

$g_{ijv} = $ cost per $km \cdot m^3$ from i to j, using vehicle type v

$co_{ij} = $ cost of opening the link between i and j

We use the classic distinction between fixed and variable costs. For example, the fixed cost of a warehouse is considered to be incurred once, if we use the warehouse. The variable cost of the warehouse is a function of the quantity sent to the warehouse.

fc_W = fixed cost to open and operate warehouse w

fc_h = fixed cost to open and operate potential warehouse h

vch_W = handling cost of warehouse w/m^3

vc_W = inventory cost of warehouse w/m^3

vc_h = inventory cost of potential warehouse h/m^3

vch_h = handling cost of potential warehouse h/m^3

cv_{mr} = cost of one m^3 of material type m in supplier r

cpp_{pl} = cost to produce a m^3 of product p in plant l

as_i = available space in entity i (m^3)

cs_{rmt} = capacity of supplier r for material type m (in m^3)

cp_l = capacity of plant l to produce finished products (in m^3)

rw_{mp} = quantity of material type m required to produce a m^3 of product p

tc_v = capacity of vehicle v (in m^3)

5.2.3. Decision Variables

With this model we want to decide about:

a) the quantities of goods k that are to be moved between any two entities, by vehicle type v, under event e (q_{kijve});

b) where each product should be produced (u_{pcl});

c) if we should open new facilities, and where these should be located (x_h);

d) the connections that should be established, under event e (y_{kije});

e) which warehouses we should use (z_w).

The decision variables q and y are contingent, as they represent values that can be changed in the future depending on the supply chain behavior. The decision variables u_{pcl} are structural as they cannot be changed after the start of production, due to the costs directly associated to such changes (this assumption is based on the requirements of the case study but can be considered to be quite general).

$\mathrm{q_{kijve}}$ = quantity of k sent from entity i to j by vehicle type v (in $\mathrm{m^3}$) under event e

$$\mathrm{y_{ije}} = \begin{cases} 1, \text{if a link from i to j is established under event e} \\ 0, \text{otherwise} \end{cases}$$

$$\mathrm{u_{pcl}} = \begin{cases} 1, \text{if product p of customer c is produced in plant l} \\ 0, \text{otherwise} \end{cases}$$

$$\mathrm{x_h} = \begin{cases} 1, \text{if new warehouse h is open} \\ 0, \text{otherwise} \end{cases}$$

$$\mathrm{z_w} = \begin{cases} 1, \text{if warehouse w is used} \\ 0, \text{otherwise} \end{cases}$$

5.2.4. Objective Functions

In this work, we have considered multiple objective functions, reflecting the main practical concerns identified in the case study and in the literature review. The following functions have been defined.

$$\begin{aligned} min\ \mathrm{f_1} = \sum_{e\in E\backslash\{0\}} \Bigg(& \sum_{j,i,k,v} \mathrm{g_{ijv}d_{ij}ir_{ei}q_{kijva(e)}} + \sum_{m,r,j,v} \mathrm{cv_{mr}ir_{er}q_{mrjva(e)}} \\ & + \sum_{p,l,j,v} \mathrm{cpp_{pl}ir_{el}q_{pljva(e)}} \\ & + \sum_{w} \mathrm{ir_{ew}} \left(\mathrm{vc_w} \sum_{k,i,v} \mathrm{q_{kiwva(e)}} + \mathrm{vch_w} \sum_{k,i,v} \mathrm{q_{kiwva(e)}} \right) \\ & + \sum_{h} \mathrm{ir_{eh}} \left(\mathrm{vc}_h \sum_{k,i,v} \mathrm{q_{kiwva(e)}} + \mathrm{vch_h} \sum_{k,i,v} \mathrm{q_{kiwva(e)}} \right) \\ & + \sum_{i,j} \mathrm{co_{ij}y_{ija(e)}\, ir_{ei}} \Bigg) Pb_e + \sum_{w} \mathrm{fc_w z_w} + \sum_{h} \mathrm{fc_h x_h} \end{aligned} \tag{1}$$

$$min\,\mathrm{f_2} = \sum_{\mathrm{h}} - \mathrm{cb_h\ x_h} \tag{2}$$

$$min\,\mathrm{f_3} = \sum_{\mathrm{e,h}} \mathrm{cl_h ir_{eh} Pb_e\ x_h} \tag{3}$$

Objective (1) consists in the minimization of the expected value of the total cost to operate the supply chain, and comprises the transportation costs, the costs of establishing links between two entities, the costs of materials required for the production of finished products, the production costs, as well as the fixed and variable costs with advanced warehouses. Objectives (2) and (3) are related with the choice of locations for new advanced warehouses, and are based on the "easiness of doing business" and the "labor costs" of each geographic zone, when deciding about future investments and taking into account an uncertainty factor – the inflation rate.

Our model will consider an aggregation of these objective functions, after an adequate normalization process of the three different components:

$$f = \alpha f_1 + \beta f_2 + \gamma f_3 \, , \alpha + \beta + \gamma = 1 \, , \alpha, \beta, \gamma \geq 0.$$

The manipulation of the "weights" will allow a sensitivity analysis, which will hopefully significantly support the decision-making process.

5.2.5. CONSTRAINTS

$$\sum_{w,v} q_{pwcve} + \sum_{h,v} q_{phcve} + \sum_{l,v} q_{plcve} = df_{cpt(e)} \qquad \forall c, p, e \in E_{T-1} \tag{4}$$

$$\sum_{w,v} q_{mwlve} + \sum_{h,v} q_{mhlve} + \sum_{r,v} q_{mrlve} = \sum_{p,c} \left(df_{cpt(e)} rw_{mp} u_{pcl} \right) \quad \forall m, l, e \in E_{T-1} \tag{5}$$

$$\sum_{r,v} q_{mrwve} = \sum_{l,v} q_{mwlve} \qquad \forall w, m, e \in E_{T-1} \tag{6}$$

$$\sum_{l,v} q_{plwve} = \sum_{c,v} q_{pwcve} \qquad \forall w, p, e \in E_{T-1} \tag{7}$$

$$\sum_{r,v} q_{mrhve} = \sum_{l,v} q_{mhlve} \qquad \forall h, m, e \in E_{T-1} \tag{8}$$

$$\sum_{l,v} q_{plhve} = \sum_{c,v} q_{phcve} \qquad \forall h, p, e \in E_{T-1} \tag{9}$$

$$y_{iwe} \leq z_w \qquad \forall i, w, e \in E_{T-1} \tag{10}$$

$$y_{wie} \leq z_w \qquad \forall i, w, e \in E_{T-1} \tag{11}$$

$$y_{ihe} \leq x_h \qquad \forall i, h, e \in E_{T-1} \tag{12}$$

$$y_{hie} \leq x_h \qquad \forall i, h, e \in E_{T-1} \tag{13}$$

$$M y_{ije} \geq q_{kijve} \qquad \forall i, j, k, v, e \in E_{T-1} \tag{14}$$

$$M u_{pcl} \geq q_{pljve} \qquad \forall p, c, l, j, v, e \in E_{T-1} \tag{15}$$

$$\sum_{p,j,v} q_{pljve} \leq cp_l \quad \forall l, e \in E_{T-1} \tag{16}$$

$$\sum_{k,i,v} q_{kijve} \leq as_j \qquad \forall j, e \in E_{T-1} \tag{17}$$

$$\sum_{j,v} \mathrm{q}_{\mathrm{mrjve}} \leq \mathrm{cs}_{\mathrm{mr}} \qquad \forall \mathrm{r}, \mathrm{m}, \mathrm{e} \in E_{T-1} \tag{18}$$

$$\sum_{l} \mathrm{u}_{\mathrm{pcl}} = 1 \qquad \forall \mathrm{p}, \mathrm{c} \tag{19}$$

$$\mathrm{q}_{\mathrm{kijve}} \geq 0, \forall \mathrm{k}, \mathrm{i}, \mathrm{j}, \mathrm{v}, \mathrm{e} \in E_{T-1} \tag{20}$$

Constraints (4) guarantee that all customer demands, for all products, are satisfied. Constraints (5) ensure that plants receive enough materials to produce the required quantity of products. Constraints (6), (7), (8) and (9) impose the conservation of flows in the entire supply chain (see Figure 24). These flows can only be established between two open entities (constraints (10), (11), (12) and (13)). Constraints (14) impose that we only ship goods through links that are open (M being an upper bound on the maximum quantity shipped). Constraints (15) impose that we only produce a product in a plant previously selected for its production.

Constraints (16) guarantee that plants cannot produce more than the installed capacity. Constraints (17) guarantee that plants and warehouses cannot receive more raw-materials and/or products than capacity available. Finally, constraints (18) are similar, for the suppliers that cannot deliver more than their own capacity.

The last constraints (19) assure that a product for a given customer will only be produced by one plant. Constraints (20) guarantee that production and transportation quantities are non-negative.

5.3. Experimental evaluation

5.3.1. Numerical Example

The developed approach was validated and assessed with a relatively small numerical example inspired by the case study. We assume a company has a supply chain with 2 suppliers (r), 3 customers (c), 1 advanced warehouse (w), 2 plants (with warehousing and production) (l), 2 potential locations for opening new advanced warehouses (h), 4 finished products (p), 3 main raw-materials (m) and 3 types of vehicles.

We have developed three different situations to study the behavior of the model under uncertainty. Figures 25, 26 and 27 show the joint evolution of the inflation rate (IR) for each "country" (there are two countries in the example). In the first and second situations we consider a stochastic evolution of the IR, whereas the third is deterministic (with a constant IR).

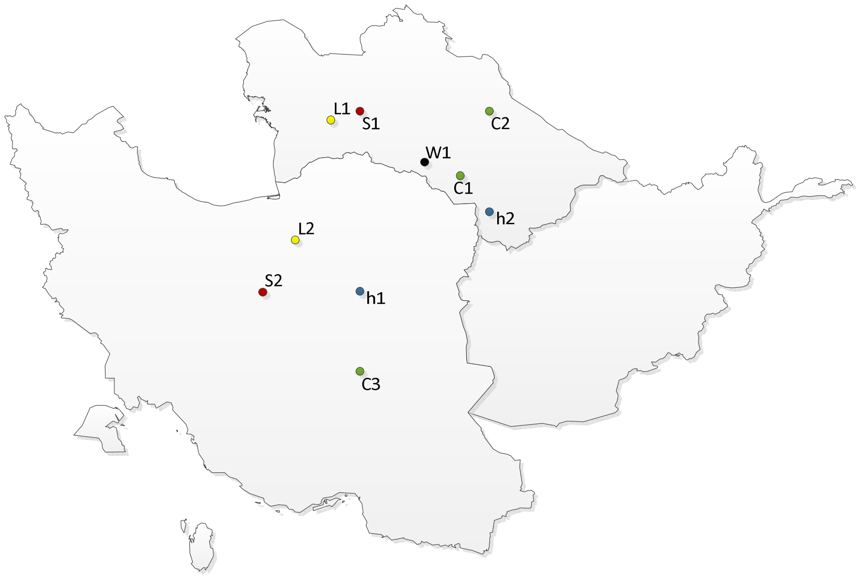


Figure 24: Supply Chain

The uncertainty parameter studied was the inflation rate, defined per each geographic zone. We have developed 3 different situations to study the behavior of the model under uncertainty and didn't. The following Figures show the inflation rate (IR) per "country" (there are two countries in the example). In the first and second situations we used different tendency to each period (stochastic scenarios), but in the other situations the IR is the same for all periods (deterministic scenario).

Situation 1

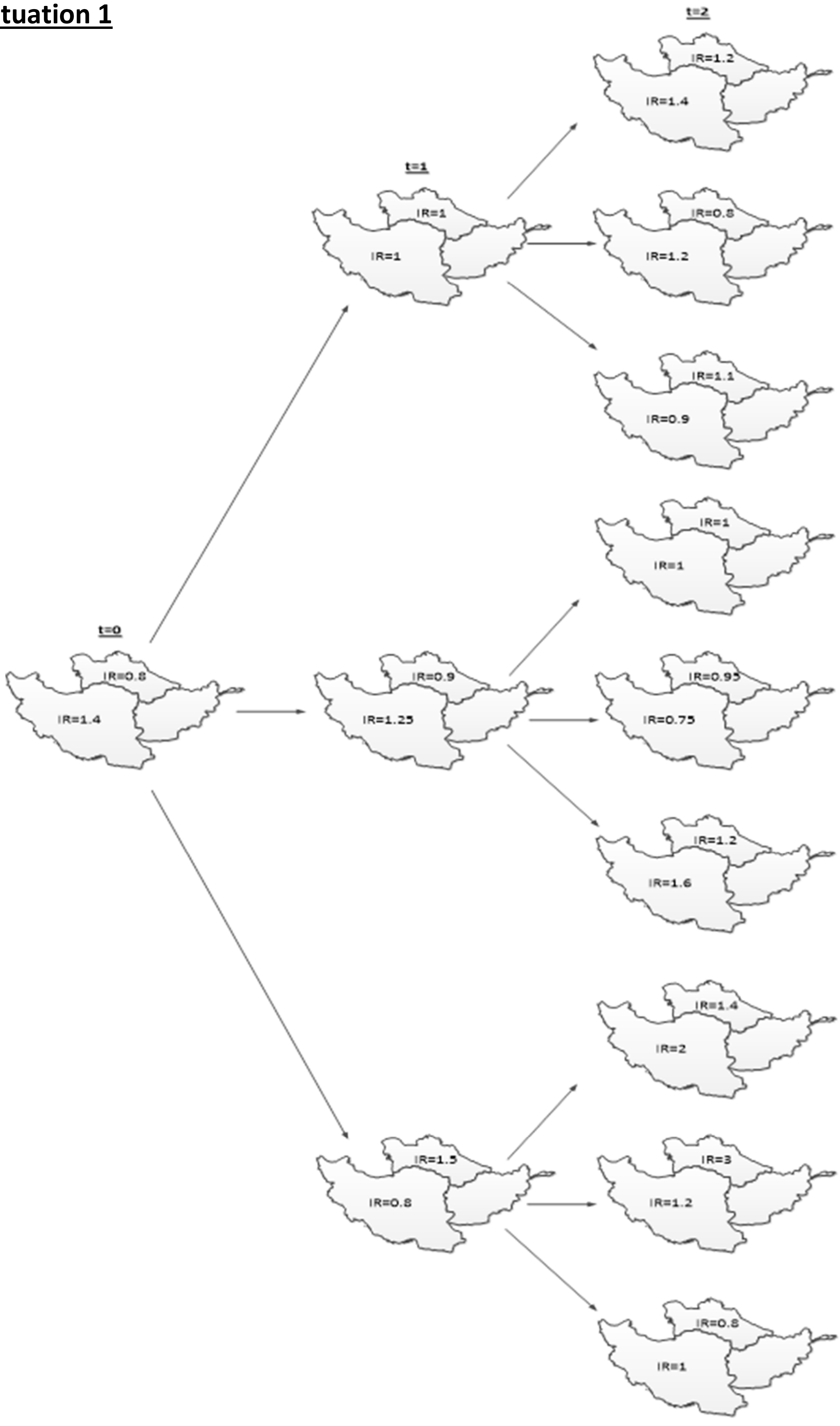


Figure 25: Situation 1

Situation 2

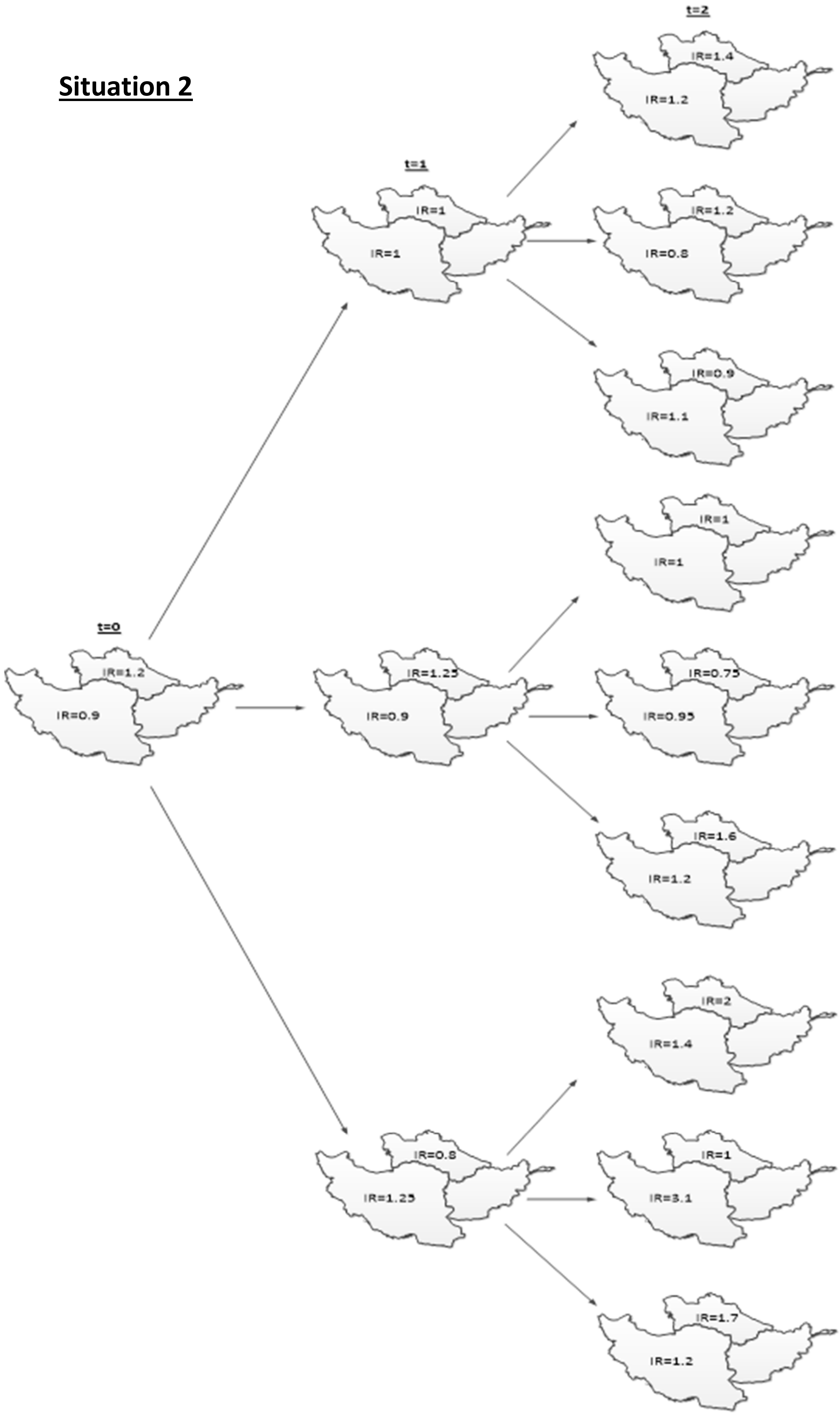


Figure 26: Situation 2

Situation 3

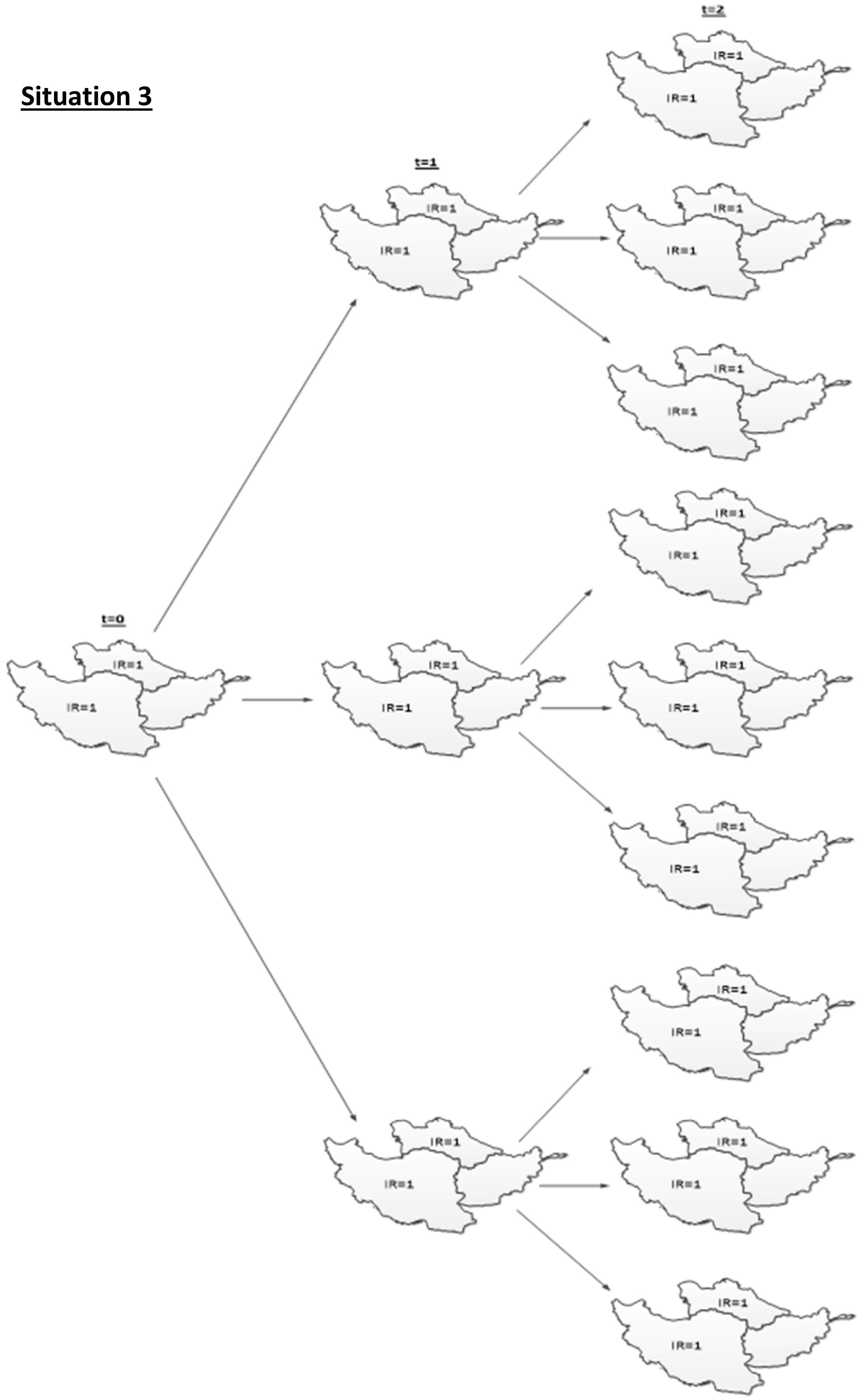


Figure 27: Situation 3

The probability associated with each event is shown in Figure 28.

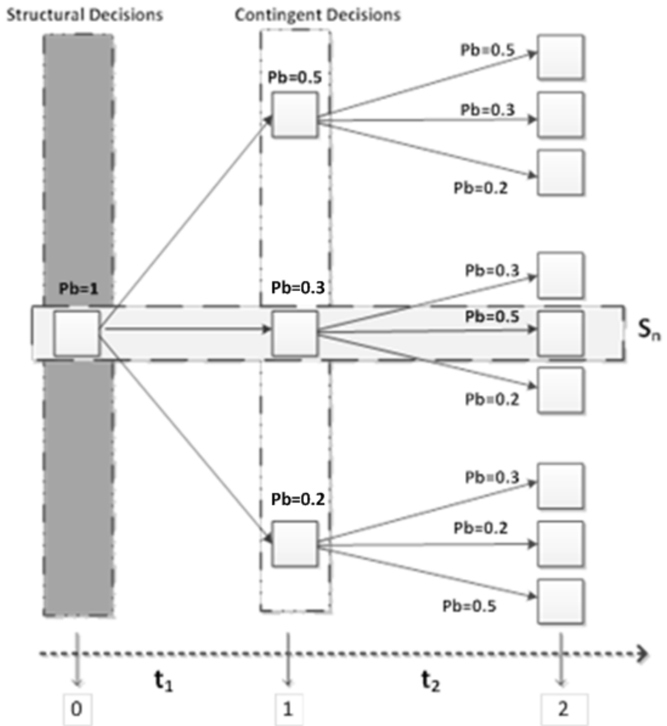


Figure 28: Probabilities of each event

Table 6 describes the demand for the different products and periods. The production of product PA starts only in period 1, as it is associated to a new project. The production of product PB decreases with time, possibly because it is a project in the end of its life cycle. The other two products present a typical demand pattern for the automotive industry.

Table 6: Demand

Customer	Product	Period	Demand
C1	**PA**	0	0
		1	120
		2	120
	PB	0	100
		1	75
		2	0
C2	**PC**	0	70
		1	70
		2	70
C3	**PD**	0	200
		1	200
		2	250

Table 7 describes the capacity of each supplier for the different raw-materials and periods.

Table 7: Supplier' Capacity

Supplier	Raw Material	Period	Demand
S1	**RM2**	0	200
		1	200
		2	200
	RM3	0	50
		1	200
		2	200
S2	**RM1**	0	100
		1	150
		2	150
	RM2	0	300
		1	350
		2	400
	RM3	0	500
		1	400
		2	300

Figure 30 shows the bill-of-materials of each product.

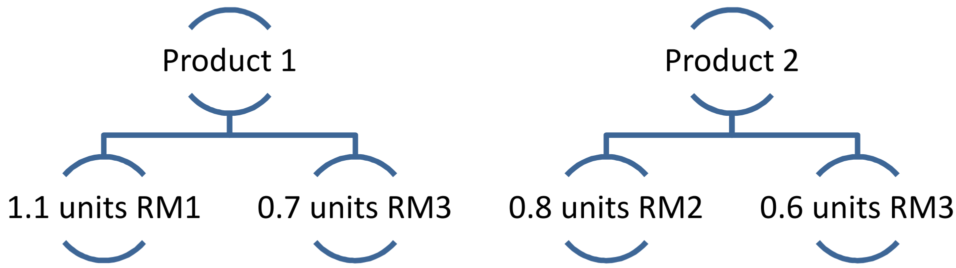


Figure 29: Bill of Materials

The detailed data used for this study can be found in Annex 1.

5.3.2. COMPUTATIONAL RESULTS

We have run a set of computational experiments on this example, with IBM ILOG CPLEX Optimizer Studio version 12.2, to study the impact of uncertainty on the inflation rate.

Table 8: Data of the test instances

	Int. variables/ Cont. variables/ Constraints	Value of Linear Relaxation	Iterations	Integrality gap[%]	Objective	CPU Time (sec.)
Situation 1		0.1681	883	0	0.21	78
Situation 2	1096/4337/7230	0.2154	972	0	0.17	82
Situation 3		0.1069	1023	0	0.18	104

All computations were run using the Branch and Bound algorithm available on the IBM ILOG CPLEX Optimizer Studio version 12.2 on a PC Intel® Core™2Duo CPU U9400 1.4GHz and 3 GB RAM under Windows 7 Professional SP1. For each situation a normalization of the objective function was performed and the optimal situation was obtained. In table 8 we summarize the data of the four situations.

In a first phase of the experimentation, we ran the model several times with different inputs, to test the practical performance of the developed model. The results obtained were always plausible from a practical perspective. To allow a solution assessment and validation by the users, the solutions for each situation were partially represented in a graphical way (Figures 30, 31 and 33) with values associated to each link, thus enabling a comprehensive analysis involving costs, capacities and requirements.

As expected, in the obtained solutions, warehouses are not used, due to their large costs. But when we add an additional constraint bounding the maximum distance between company facilities and markets, H1 is opened and used. This constraint is quite plausible for industrial companies. We observed that this also happens due the smaller variation in the inflation rate in “Country2” (where H1 is located). So, the cost decreases and the production increases in L2, and therefore an additional warehouse is required since the capacity is not enough.

The costs represented in table 9 are related with the base formulation (without the distance constraint). Situation 1 is the worst (more expensive). In this situation the costs were 1.684.500 € for transportation (a normal value) 8.800 € for establishing links between two entities, 38.376 € for raw-materials and 833,97 € for production. The warehousing cost is 0 as no warehouse has been opened or is being used. The objective functions related with new locations (developed to minimize current and future costs with new warehouses) have a value of 0 for the easiness of doing business and the labor cost.

As expected, for each situation the structure of the supply chain is different, due the inflation rate and to the considered probabilities, changing the future cost of production in each plant and the total cost of the transportation network.

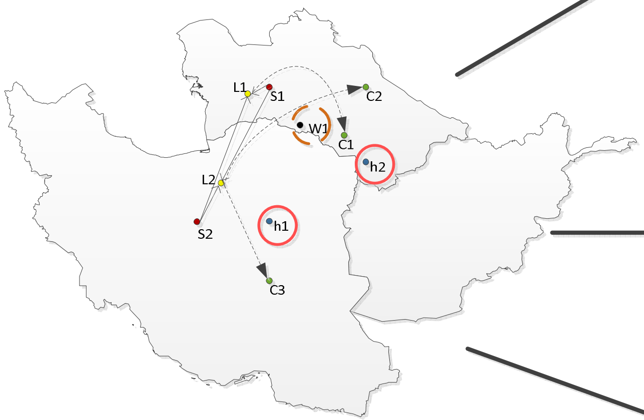
In some events, plant L1 is deactivated, because the costs in “country2” are more favorable. In situations 2 and 3, plant L1 is not used in any event due the high inflation rate in “country1”.

This is only a small example used to partially illustrate how industrial companies operate, but all the results were discussed and validated in the company with the people involved in the project. Changing the values of probabilities for each scenario was also helpful to allow the users to assess the impact of uncertainty in the different objectives.

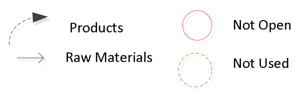
Table 9: Costs of each situation

Objective Functions	**Situation 1**	**Situation 2**	**Situation 3**
Transportation	1.684.500	1.542.560	1.616.038
Links	8.800	9.004	8.524
Raw-Materials	38.376	37.475	35.752
Production	833,97	987	789,6
Warehouses	0	0	0
Cost (f1)	1.732.509,97	1.590.026	1661103.6
Easiness of Doing Business (f2)	0	0	0
Labor Costs (f3)	0	0	0

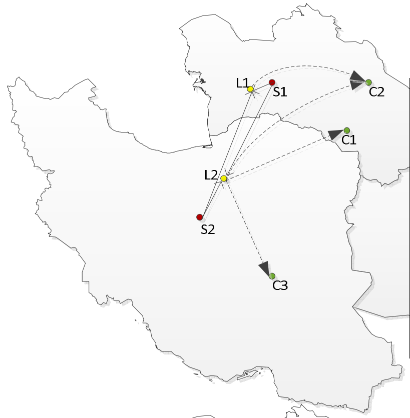
k	i	j	v	e	Value
PB_C1	L1	C1	V3	e0	100
PC_C2	L2	C2	V1	e0	70
PD_C3	L2	C3	V2	e0	200
RM1	S1	L2	V1	e0	160
RM2	S1	L2	V1	e0	70
RM2	S1	L1	V1	e0	60
RM3	S2	L2	V1	e0	169
RM3	S1	L1	V1	e0	80



Event 0

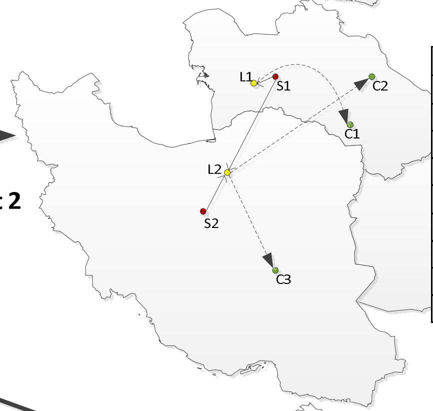


Event 1



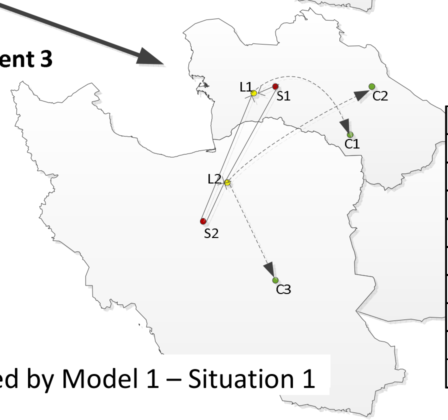
k	i	j	v	e	Value
PA_C1	L2	C1	V1	e1	120
PB_C1	L1	C1	V3	e1	75
PC_C2	L2	C2	V1	e1	70
PD_C3	L2	C3	V3	e1	200
RM1	S1	L2	V1	e1	280
RM2	S2	L2	V1	e1	154
RM2	S1	L1	V1	e1	45
RM3	S2	L2	V1	e1	169
RM3	S1	L1	V1	e1	60

Event 2



k	i	j	v	e	Value
PA_C1	L2	C1	V3	e2	120
PB_C1	L1	C1	V1	e2	75
PC_C2	L2	C2	V3	e2	70
PD_C3	L2	C3	V3	e2	200
RM1	S1	L2	V1	e2	280
RM2	S1	L2	V2	e2	154
RM2	S1	L1	V1	e2	45
RM3	S1	L2	V2	e2	169
RM3	S1	L1	V1	e2	60

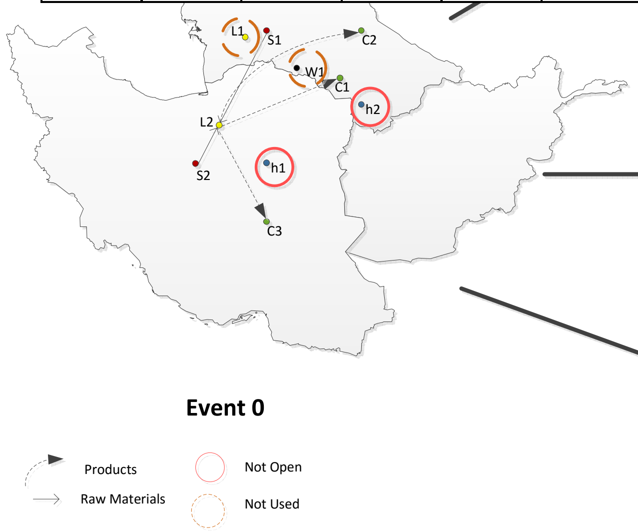
Event 3

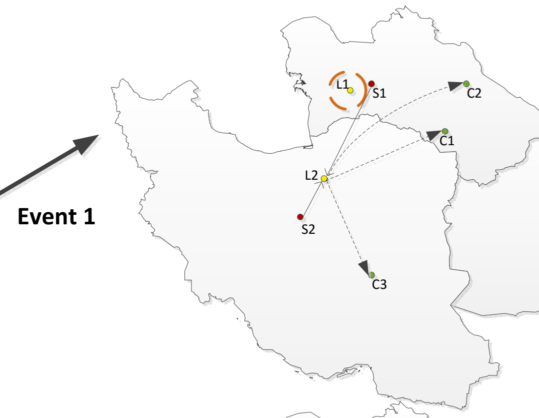


k	i	j	v	e	Value
PA_C1	L2	C1	V3	e3	120
PB_C1	L1	C1	V3	e3	75
PC_C2	L2	C2	V3	e3	70
PD_C3	L2	C3	V3	e3	200
RM1	S1	L2	V1	e3	280
RM2	S1	L2	V1	e3	154
RM2	S1	L1	V2	e3	45
RM3	S2	L2	V2	e3	169
RM3	S2	L1	V2	e3	60

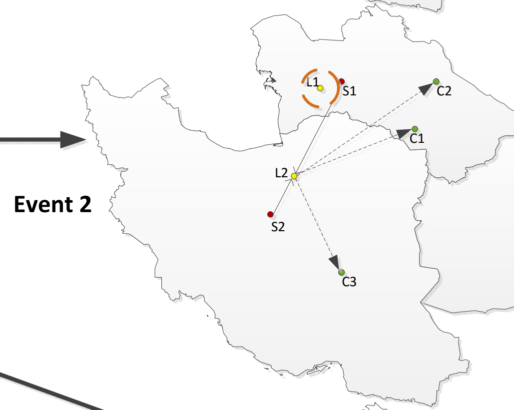
Figure 30: Results obtained by Model 1 – Situation 1

k	i	j	v	e	Value
PB_C1	L2	C1	V3	e0	100
PC_C2	L2	C2	V1	e0	70
PD_C3	L2	C3	V1	e0	200
RM1	S1	L2	V1	e0	160
RM2	S2	L2	V3	e0	130
RM3	S2	L2	V1	e0	249

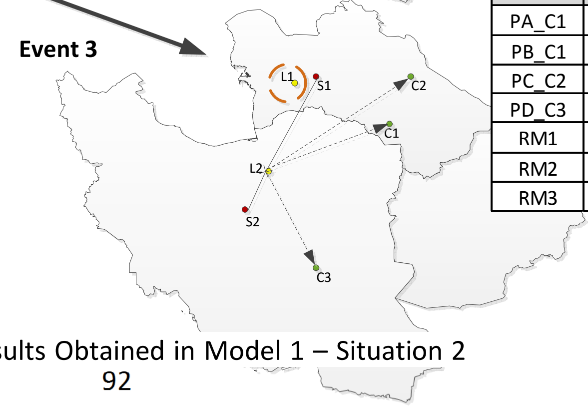




k	i	j	v	e	Value
PA_C1	L2	C1	V3	e1	120
PB_C1	L2	C1	V2	e1	75
PC_C2	L2	C2	V3	e1	70
PD_C3	L2	C3	V3	e1	200
RM1	S1	L2	V2	e1	280
RM2	S2	L2	V2	e1	199
RM3	S2	L2	V2	e1	229



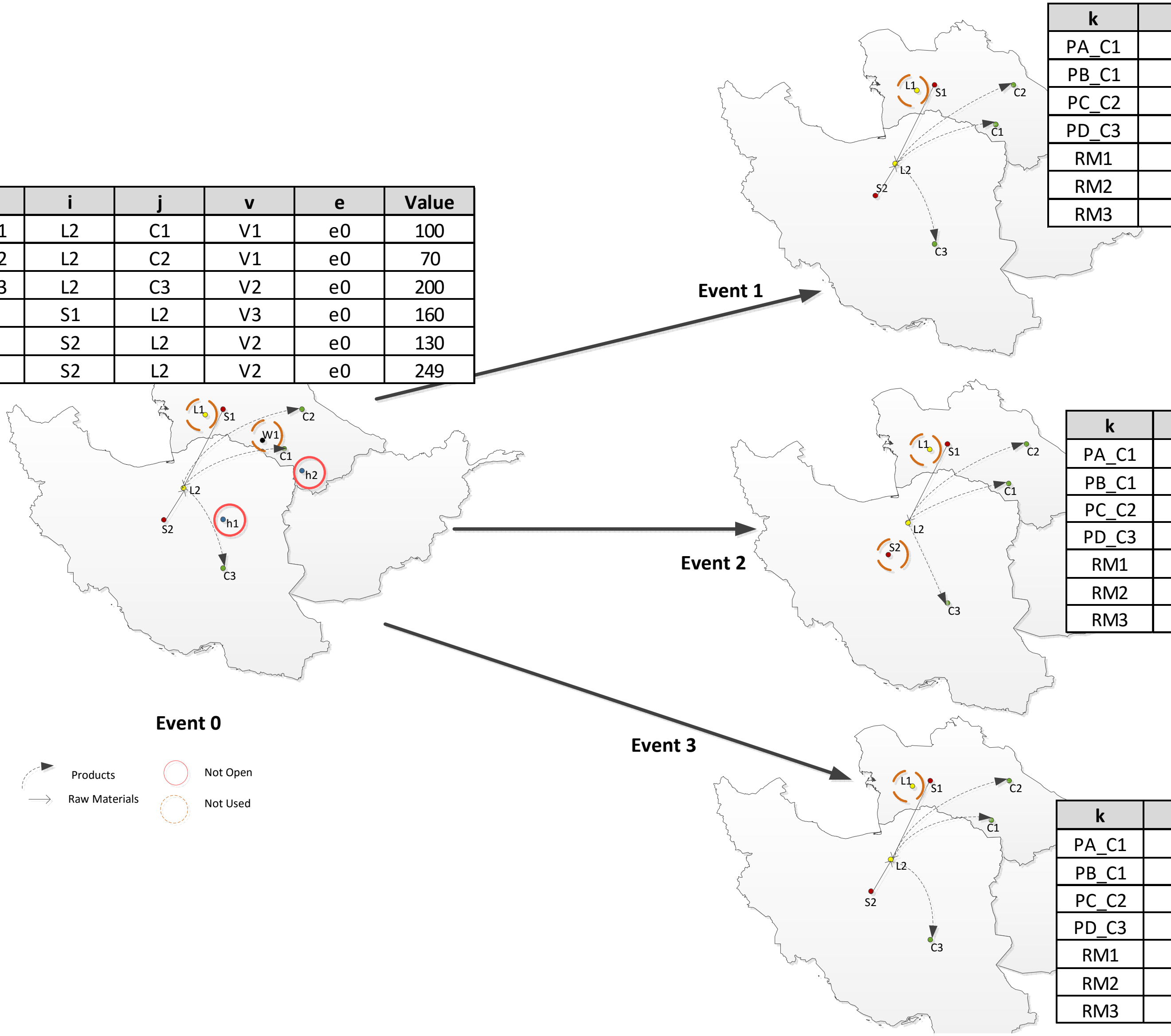
k	i	j	v	e	Value
PA_C1	L2	C1	V2	e2	120
PB_C1	L2	C1	V2	e2	75
PC_C2	L2	C2	V1	e2	70
PD_C3	L2	C3	V1	e2	200
RM1	S1	L2	V1	e2	280
RM2	S1	L2	V1	e2	199
RM3	**S2**	L2	**V2**	**e2**	229



k	i	j	v	e	Value
PA_C1	L2	C1	V2	e3	120
PB_C1	L2	C1	V1	e3	75
PC_C2	L2	C2	V1	e3	70
PD_C3	L2	C3	V1	e3	200
RM1	S1	L2	V3	e3	280
RM2	S2	L2	V1	e3	199
RM3	S2	L2	V1	e3	229

Figure 31: Results Obtained in Model 1 – Situation 2

k	i	j	v	e	Value
PB_C1	L2	C1	V1	e0	100
PC_C2	L2	C2	V1	e0	70
PD_C3	L2	C3	V2	e0	200
RM1	S1	L2	V3	e0	160
RM2	S2	L2	V2	e0	130
RM3	S2	L2	V2	e0	249



k	i	j	v	e	Value
PA_C1	L2	C1	V2	e1	120
PB_C1	L2	C1	V3	e1	75
PC_C2	L2	C2	V1	e1	70
PD_C3	L2	C3	V2	e1	200
RM1	S1	L2	V2	e1	280
RM2	S2	L2	V2	e1	199
RM3	S2	L2	V2	e1	229

k	i	j	v	e	Value
PA_C1	L2	C1	V1	e2	120
PB_C1	L2	C1	V1	e2	75
PC_C2	L2	C2	V3	e2	70
PD_C3	L2	C3	V1	e2	200
RM1	S1	L2	V1	e2	280
RM2	S1	L2	V1	e2	199
RM3	S1	L2	V2	e2	229

k	i	j	v	e	Value
PA_C1	L2	C1	V2	e3	120
PB_C1	L2	C1	V1	e3	75
PC_C2	L2	C2	V1	e3	70
PD_C3	L2	C3	V2	e3	200
RM1	S1	L2	V2	e3	280
RM2	S1	L2	V1	e3	199
RM3	S2	L2	V1	e3	229

Figure 32: Results Obtained in Model 1 – Situation 3

5.4. Model generalization

In this work, a model has been developed for dealing with uncertainty in supply chain design in the automotive industry. In particular, this model has a stochastic nature, and can be used to support strategic-tactical decision-making.

Moreover the model covers a set of different features of real, practical environments, namely: multi-periods planning horizons, multi-criteria assessment of policies, international issues such as exchange rates, and some major specific concerns of companies. However some further work needs to be done in enhancing this model and in making it more realistic and of broader application.

The approaches that will be presented in the next section have been identified as essential for supporting decision making in operations strategy planning, and also in understanding how the supply chain network should evolve in the long term, in order to optimize the profitability of operations. For such purpose, these models require the definition of scenarios for future evolution of supply, demand, transportation and other critical elements of the supply chain network.

6. Model extensions

6.1. Approach description

The development of our first model was mainly concerned with the possible occurrence of different values and evolution of inflation rates, for different zones in Europe (e.g., Eastern Europe, Central Europe, and Iberian Peninsula) and not for the European Union as a whole. The use of inflation in this research was a first step to assess and validate a model that we have extended to deal with other uncertainty factors, simultaneously. So, we have studied the *brent* costs and also the impact of extreme events in the supply chain operation.

In previous stages of the research we have used some simplified problems, directly motivated by a first version of the case study. A second version was modeled with 4 possible extensions to the initial model.

So, taking as a basis that initial model (Model 1) we first added Extension 1 to allow decisions on changes of the stock capacity in (own or outsourced) warehouses and on the production capacity in each plant. And, we also added Extension 2 to study the possibility of opening new facilities (plants or warehouses). These two extensions in combination with Model 1 led us to Model 2.

Extensions 3 and 4 are related with the uncertainty parameters used in Model 1 (only concerning the inflation rate) and the new parameters (*brent costs and extreme events)*. The combinations of these last two extensions resulted in Model 3.

In a first approach, and in order to proceed incrementally, we have studied the different extensions separately, and afterwards we have analyzed the possibility of including all types of decisions and uncertainty parameters in our case study.

Considering the different extensions and the assessment of the final, integrated model, we have created several problem instances with specific data collected in the case study. The final model (Model 3) is a multi-period, multi-objective (minimization of cost, maximization of potential new businesses), bi-stage decision (strategic level decisions, tactical level decisions) model. It is a stochastic model based on a scenario tree approach. Nevertheless there are still some limitations in the developed approach, which will be duly explained later in this chapter.

Figure 30 shows the design process followed during the development of this model.

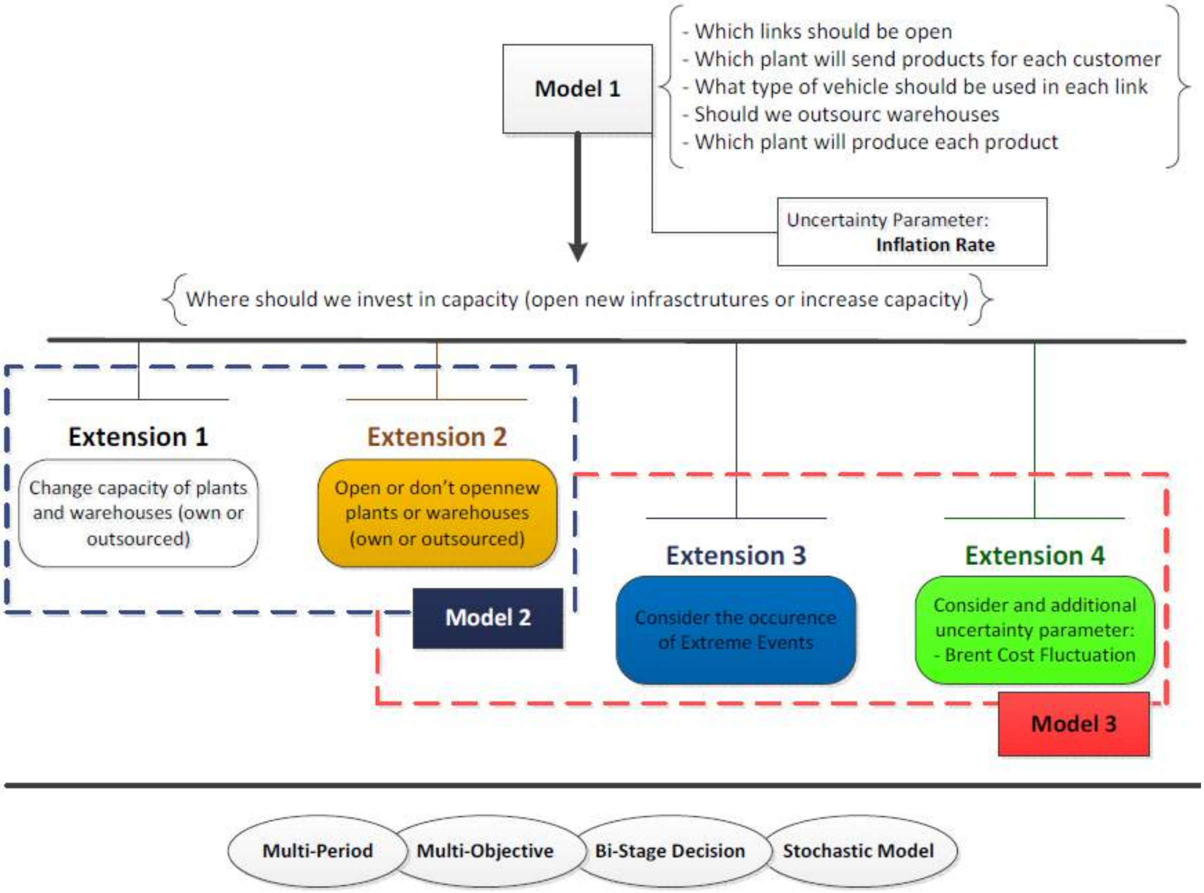


Figure 33: Final Model

As in the previous model, let us assume a company has a typical supply chain with suppliers (r), customers (c), advanced warehouses (w), plants (warehousing and production) (l), potential locations for opening new warehouses and plants (h), finished products (p) and raw-materials (m). Figure 31 schematically represents the type of connections established between all members of this supply chain.

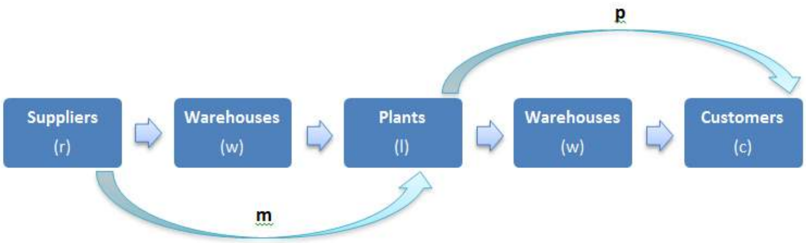


Figure 34: Example of a supply chain network

Suppliers (r) are companies that can send raw materials and components to warehouses or directly to the plants. Warehouses (w) are all storage units that are not located at the production units (plants), so they can be advanced warehouses or distribution centers. These entities can receive materials (m) from suppliers and can send finished products (p) to customers. For this reason they are duplicated in this representation of the supply chain structure. Warehouses are always linked to plants (they send raw materials/components and they receive finished products). Plants (l) are all units of production (they convert raw materials/components into finished products) that belong to the supply chain under study. In plants we also find (internal) warehouses for raw materials and finished products. Customers (c) are the last entities in the supply chain - they receive finished products from plants and/or warehouses.

Materials (m) are raw-materials, components, sub-components used in the production process of finished products. Products (p) are finished products sent to customers. The potential locations (h) are “suggestions” for new geographic locations that can possibly be included in the current supply chain. A new location could be a distribution center/warehouse or a plant closer to the customers and/or suppliers. According to the company’s strategy, the new warehouses can be acquired, leased or “subcontracted”.

Trying to minimize the total costs to operate the supply chain, the model should decide about the quantity to move between any two entities, where each product should be produced, if we should open new facilities, where these should be located (network design), and if we should increase the capacities (of the plants or the warehouses). The model should also define the connections to be established, which warehouses to use, the quantity of each material required by the different production processes, and how to transport the materials and finished products (mode).

This (dynamic) model is characterized by two decision stages, in order to explicitly consider uncertainty. In the example, we will consider several possible scenarios (s) taking into account different inflation rate evolutions in the two considered periods.

Each scenario (s) involves two events (e), one per each time period (t) between the stages. An event is an evolution of the uncertainty factors under consideration – in this case, only the “inflation rate” is considered. Each event has associated a probability of occurrence Pb_e. In extension 4 of the model, we add an extra uncertainty parameter related with the *brent* cost fluctuation, thus considering a model with two uncertainty parameters. In extension 3 we consider a set of parameters to represent extreme uncertainty (e.g., catastrophic events) not related with “regular” uncertainty.

6.1.General Approach

As referred, we have structured the model around two decision stages, with uncertainty modeled over scenarios s with a specific probability of occurrence associated.

For illustration purposes, we will consider an example where a scenario s (s = 1, 2, …) is a path in a scenario tree, with a set of nodes, one in each instant of time. We will also consider periods t (t = 0, 1, …, T) that are intervals of time between two instants.

In this work, the paradigm chosen to deal with uncertainty was the "scenario tree", with conditional probabilities associated to each scenario, i.e., the probability of each branch depends on what has happened in the previous periods.

If we consider 3 instants and 2 time periods (t1- between instants 0 and 1; t2 - between instants 1 and 2), and 3 different uncertainty behaviors (one per branch), we will have 9 different scenarios as shown in Figure 32.

Each node represents an event e (the result of the evolution of the uncertainty factor in a specific period) and it has associated a probability of occurrence Pb_e.

$$\mathrm{e} \in \mathrm{E}: \text{ events} \qquad\qquad \mathrm{e} = 0,1,2,\ldots$$

We also consider a(e) as one of the antecedent nodes of event e, and t(e) as the time instant of event e. To simplify our notation we define subsets of events:

$$E_{t'} = \{e \in E : t(e) \leq t'\}$$

So, a probability distribution for the inflation (the uncertainty factor considered here) is specified for the geographic location of each customer. The model gives us the location of facilities to open, the capacities required to satisfy the demand, which facilities should we use, and the quantities that should be moved between any two entities. These decisions aim at minimizing the expected costs, considering transportation, warehousing, production and new investments in capacity.

We consider here a discretized planning horizon (in the case study, the horizon is divided into semesters).

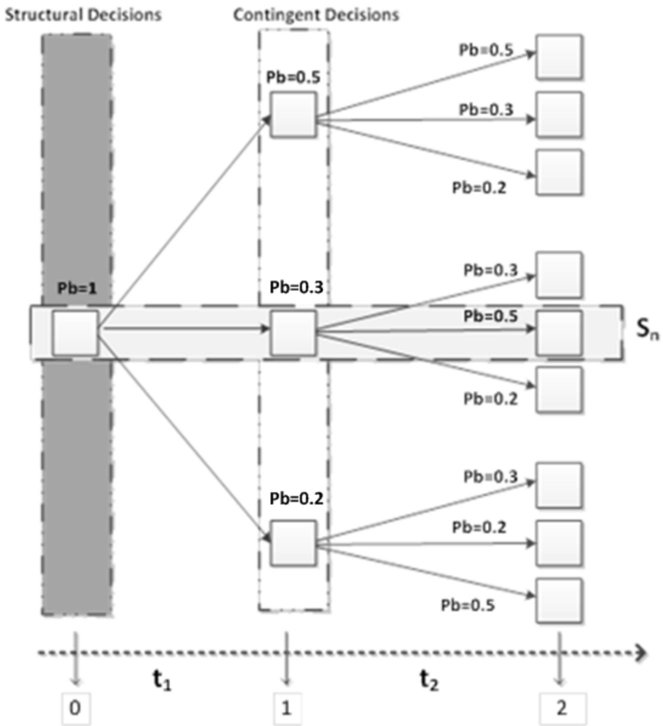


Figure 35: Scenario Tree

So, in instant 0 we will take decisions about the network configuration and flows of goods for time period t1. In instant 1 we will decide again, based on the value of the uncertainty factor, but only about flows, thus assuming the network configuration is very complex and expensive to be changed.

6.2. Mathematical Models

6.2.1. Indices

As referred previously, the supply chain network is defined as a set of entities, and a set of arcs that establish connections between pairs of entities and represent the flows of products across the supply chain.

$r \in R = Suppliers$	$r = 1,2,3,\ldots$
$c \in C = Customers$	$c = 1,2,3,\ldots$
$w \in W = Warehouses$	$w = 1,2,3,\ldots$
$l \in L = Plants$	$l = 1,2,3,\ldots.$
$h \in H = Potential\ locations\ for\ new\ warehouses\ and\ plants$	$h = 1,2,3,\ldots$

The potential locations for new facilities (h) are suggestions for sites where it may be interesting to locate new infrastructures (to be included in the current supply chain). A new facility could be a distribution center / warehouse (w'') or a plant (l'') that for instance allows operations closer to the customers and/or suppliers. According to the company's strategy, the new warehouses can be acquired, leased or "subcontracted".

So, we consider a set of warehouses (W) with current warehouses (W') and potential new warehouses (W''), and we consider a group of plants (L) with current plants (L') and potential new plants (L''):

$$\mathrm{w} \in \mathrm{W} = \{\mathrm{W}' \cup \mathrm{W}''\}$$

$$\mathrm{l} \in \mathrm{L} = \{\mathrm{L}' \cup \mathrm{L}''\}$$

Each plant has a level of production capacity (γ or σ), measured in m3/year. The warehouses also have a level of capacity available space (φ or β), measured in m^3.

$$\gamma, \sigma = Level\ of\ production\ capacity\ increase\ of\ Plants \qquad \gamma, \sigma = 1,2,3$$

$$\varphi, \beta = Level\ of\ capacity\ increase\ of\ Warehouses \qquad \varphi, \beta = 1,2,3$$

To simplify the notation, we will in general assume that flows occur between an origin i and a destination j (these may represent homogeneous geographic zones, rather than specific locations).

$$\mathrm{i} \in \mathrm{I} = \{\mathrm{R} \cup \mathrm{W} \cup \mathrm{L} \cup \mathrm{H}\}$$

$$\mathrm{j} \in \mathrm{J} = \{\mathrm{W} \cup \mathrm{L} \cup \mathrm{H} \cup \mathrm{C}\}$$

We will also consider parameters related to the bill-of-materials, namely the type of materials (m) required to produce the final products (p). Each type of finished product requires the same types of resources.

$$\mathrm{m} \in \mathrm{M} = \text{types of materials for production} \qquad \mathrm{m} = 1,2,3, ..$$

$$\mathrm{p} \in \mathrm{P} = \text{types of finished products} \qquad \mathrm{p} = 1,2,3 \ldots$$

These materials will also be grouped into a set K of goods, to simplify the notation in some parts of the model.

$$k \in K = M \cup P$$

Each type of vehicle is associated to a different cost per usage (tariff). This cost depends on the dimensions, mode and route (origin and destination). The set V represents all types of vehicles considered in this model.

$$v \in V = \text{vehicle types} \qquad\qquad v = 1, 2, \ldots$$

6.2.2. Parameters

$ir_{ei} =$
expected increase in annual inflation rate in the geographic zone of entity i under event e (in %)

$Pb_e =$ probability of occurrence of event e

$d_{ij} =$ distance between entities i and j (in km)

$d_{max} =$ distance between entities i and j (in km)

$cb_h =$ business potential of geographic location h (scale: 1 to 5)

$df_{cpt} =$ demand for customer c of product p (in m^3) in the time period beginning at t

$cl_h =$ labor cost in geographic location h (€/month)

$g_{ijv} =$ cost per km . m^3 from i to j, using vehicle type v

$co_{ij} =$ cost of opening the link between i and j

Some parameters will be considered “fixed” because they do not depend on quantities, and other parameters will be “variable” as their values change with quantities. For example, the fixed cost of warehouse w is a cost incurred once if we use the warehouse. The variable cost of the warehouse is a function of the quantity sent to the warehouse.

$fc_{w\beta} =$ fixed cost to operate warehouse w with capacity β

$fc_{l\sigma} =$ fixed cost to operate plant l with capacity σ

vch_W = handling cost of warehouse w/m^3

vc_W = inventory cost of warehouse w/m^3 per *period*

cv_{mr} = cost of one m^3 of material type m in supplier r

cpp_{pl} = cost to produce one m^3 of product p in plant l

as_w = initial available space in warehouse w (m^3per period)

cs_{rm} = capacity of supplier r for material type m (in m^3)

cp_l = initial production capacity of plant l (m^3 *per year*)

rw_{mp} = quantity of material type m required to produce one m^3 of product p

$icc_{l\sigma}$ = investment for changing capacity of prodution in plant l by the quantity of level σ

$icc_{w\beta}$ = investment for changing capacity of warehouses w by the quantity of level β

cap_σ = quantity of production capacity increased associated with level σ (m^3 *per year*)

cap_β = quantity of capacity increased associated with level β (m^3 per period)

$ic_{h\sigma}$ = investment cost to open a new plant h with production capacity σ

ich_β = investment cost to open a new warehouse h with capacity β

ev_{ie} = vulnerability of geographic zone of entity i to extreme event e (scale: 1 to 5)

bc_{ie} = increase in cost of *brent* in geographic zone of entity i under event e (scale in %)

6.2.3. Decision Variables

As already referred this model is based on Model 1 with 4 possible extensions, and therefore we need to add the corresponding decisions variables.

With this model we want to decide about the quantities of goods k that should be sent between any two entities, by vehicle type v, during a time period t (q_{kijve}); where each product should be produced (u_{pcl}); if we should open new facilities and where these should be located ($x_{l\sigma e}$; $\theta_{w\beta e}$); the connections that should be established (y_{ije}); which warehouses we will use; and also on how much should we increase the capacity of existing facilities ($\partial_{we\beta}$; $\partial_{we\beta}$).

We define now these variables in greater detail:

q_{kijve} = quantity of k sent from entity i to j by vehicle type v (in m^3) under event e

$$y_{ije} = \begin{cases} 1, \text{if a link from i to j is established under event e} \\ 0, \text{otherwise} \end{cases}$$

The decision variables q and y are contingent, as they represent values that can be changed in the future depending on the supply chain behavior.

$$u_{pcl} = \begin{cases} 1, \text{if product p of customer c is produced in plant l} \\ 0, \text{otherwise} \end{cases}$$

The decision variables u_{pcl} are structural as they cannot be changed after the start of production, due to the costs directly associated to these changes (this assumption is based on the requirements of the case study).

CP_{le} = production capacity of plant l under event e (m^3)

AS_{we} = available space capacity of warehouse w under event e (m^3)

$$\alpha_{le\sigma} = \begin{cases} 1, \text{if capacity of plant l is increased by the quantity of level } \sigma \text{ under event e} \\ 0, \text{otherwise} \end{cases}$$

$$\partial_{we\beta} = \begin{cases} 1, \text{if capacity of warehouse w is increased by the quantity of level } \beta \text{ under event e} \\ 0, \text{otherwise} \end{cases}$$

$$x_{l\sigma e} = \begin{cases} 1, \text{if location l has production capacity } \sigma \text{ under event e} \\ 0, \text{otherwise} \end{cases}$$

$$\theta_{w\beta e} = \begin{cases} 1, \text{if location w has capacity } \beta \text{ under event e} \\ 0, \text{otherwise} \end{cases}$$

6.2.4. Objective Functions

Model 2

EXTENSION 1

$$\begin{aligned}
\min f_1 = \sum_{e\in E\setminus\{0\}} \Bigg(& \sum_{j,i,k,v} \mathrm{g_{ijv} d_{ij} ir_{ei} q_{kijva(e)}} + \sum_{m,r,j,v} \mathrm{cv_{mr} ir_{er} q_{mrjva(e)}} \\
& + \sum_{l,p,j,v} \mathrm{cpp_{pl} ir_{el} q_{pljva(e)}} \\
& + \sum_{w} \mathrm{ir_{ew}} \left(\mathrm{vc_w} \sum_{k,i,v} \mathrm{q_{kiwva(e)}} + \mathrm{vch_w} \sum_{k,i,v} \mathrm{q_{kiwva(e)}} \right) + \sum_{i,j} \mathrm{co_{ij} y_{ija(e)}\, ir_{ei}} \\
& + \sum_{l,\sigma} \mathrm{fc_{l\sigma}} x_{\mathrm{l\sigma a(e)}} \mathrm{ir_{el}} + \sum_{w,\beta} \mathrm{fc_{w\beta} \theta_{w\beta e} ir_{ew}} \Bigg) Pb_e \qquad \textbf{(1)} \\
& + \sum_{h,\sigma} \mathrm{ic_{h\sigma}} x_{\mathrm{h\sigma 0}} \mathrm{ir}_{0h} + \sum_{h,\beta} \mathrm{ic_{h\beta}} \theta_{\mathrm{h\beta 0}} \mathrm{ir}_{0h} \\
& + \sum_{e\in E_{T-1}\setminus\{0\}} \left(\sum_{h,\sigma} \mathrm{ic_{h\sigma}} \left(x_{\mathrm{h\sigma e}} - \sum_{\gamma} x_{\mathrm{h\gamma a(e)}} \right) \mathrm{ir}_{eh} + \right) Pb_e \\
& + \sum_{e\in E_{T-1}} \left(\sum_{l,\sigma} \mathrm{icc_{l\sigma}} \alpha_{\mathrm{le\sigma}} \mathrm{ir}_{el} + \sum_{w,\beta} \mathrm{icc_{w\beta}} \partial_{\mathrm{we\beta}} \mathrm{ir}_{ew} \right) Pb_e
\end{aligned}$$

EXTENSION 2

Decision: open or not new plants or warehouses

$$\min f_2^2 = \sum_{\mathrm{h,\sigma,e}\in E_{T-1}} - \mathrm{cb_h\ x_{h\sigma e} Pb_e} + \sum_{\mathrm{h,\beta,e}} - \mathrm{cb_h\ \theta_{h\beta e} Pb_e} \qquad \textbf{(2)}$$

$$\min f_3^2 = \sum_{\mathrm{h,\sigma,e}\in E\setminus\{0\}} \mathrm{cl_h ir_{eh} Pb_e\ x_{h\sigma a(e)}} + \sum_{\mathrm{h,\beta,e}} \mathrm{cl_h ir_{eh} Pb_e\ \theta_{h\beta a(e)}} \qquad \textbf{(3)}$$

EXTENSION 3

Uncertainty parameter: extreme events

$$minf_4 = \sum_{\mathrm{h,\sigma,e}} \mathrm{x_{h\sigma e}\ ev}_{he} + \sum_{\mathrm{h,\beta,e}} \mathrm{\theta_{h\beta e}\ ev}_{he} \qquad \textbf{(4)}$$

EXTENSION 4

Uncertainty parameter: brent cost

$$\begin{aligned}\min f_1^4 = \sum_{e \in E\setminus\{0\}} \Bigg(& \sum_{j,i,k,v} \mathrm{g_{ijv} d_{ij} ir_{ei}} bc_{ie} \mathrm{q_{kijva(e)}} + \sum_{m,r,j,v} \mathrm{cv_{mr} ir_{er} q_{mrjva(e)}} \\ & + \sum_{l,p,j,v} \mathrm{cpp_{pl} ir_{el} q_{pljva(e)}} \\ & + \sum_{w} \mathrm{ir_{ew}} \left(\mathrm{vc_w} \sum_{k,i,v} \mathrm{q_{kiwva(e)}} + \mathrm{vch_w} \sum_{k,i,v} \mathrm{q_{kiwva(e)}} \right) + \sum_{j,i} \mathrm{co_{ij} y_{ija(e)}\, ir_{ei}} \\ & + \sum_{w,\beta} \mathrm{fc_{w\beta} z_{we}} + \sum_{l,\sigma} \mathrm{fc_{l\sigma} ir_{el}} \Bigg) Pb_e \end{aligned} \quad \textbf{(5)}$$

Objective (1) consists in the minimization of the total costs to operate the supply chain, and includes the transportation costs, the costs of opening links between two entities, the costs of materials required for the production of finished products, the production costs, as well as the fixed and variable costs with plants and warehouses. Objectives (2) and (5) are related with the choice of locations for new facilities, and are based on the "easiness of doing business" and the "labor costs" of each geographic zone, when making decisions on future investments, taking into account the uncertainty parameter – the inflation rate.

Objective (1) was extended in two alternative ways - (1) and (5) - taking into account the extension of the original model as explained above. Objective (1) is only influenced by extensions 1 and 4, and therefore it is the objective function for Model 2. Finally, extension 3 provides a new objective function (4) to deal with the uncertainty parameters related to the occurrence of extreme events in each geographic zone.

Our model will consider an aggregation of these objective functions, after an adequate normalization process:

$$\mathrm{f} = \alpha \mathrm{f_1} + \beta \mathrm{f_2} + \gamma \mathrm{f_3} + \partial \mathrm{f_4}\ , \ \alpha + \beta + \gamma + \partial = 1\ , \ \alpha, \beta, \gamma, \partial \geq 0.$$

6.2.5. Constraints

$$\sum_{\mathrm{v,w}} \mathrm{q_{pwcve}} + \sum_{\mathrm{v,h}} \mathrm{q_{phcve}} + \sum_{\mathrm{v,l}} \mathrm{q_{plcve}} = \mathrm{df_{cpt(e)}} \qquad \forall \mathrm{c, p, e} \in E_{T-1} \qquad (6)$$

$$\sum_{r,v,w} \mathrm{q}_{\mathrm{mrwve}} + \sum_{r,v,h} \mathrm{q}_{\mathrm{mrhve}} + \sum_{r,v,l} \mathrm{q}_{\mathrm{mrlve}} = \sum_{p,c} \left(\mathrm{df}_{\mathrm{cpt(e)}} \mathrm{rw}_{\mathrm{mp}}\right) \quad \forall \mathrm{m}, \mathrm{e} \in E_{T-1} \tag{7}$$

$$\sum_{v,r} \mathrm{q}_{\mathrm{mrwve}} = \sum_{v,l} \mathrm{q}_{\mathrm{rwlve}} \quad \forall \mathrm{w}, \mathrm{m}, \mathrm{e} \in E_{T-1} \tag{8}$$

$$\sum_{v,l} \mathrm{q}_{\mathrm{plwve}} = \sum_{v,c} \mathrm{q}_{\mathrm{pwcve}} \quad \forall \mathrm{w}, p, \mathrm{e} \in E_{T-1} \tag{9}$$

$$\sum_{v,r} \mathrm{q}_{\mathrm{mrhve}} = \sum_{v,l} \mathrm{q}_{\mathrm{rhlve}} \quad \forall \mathrm{h}, m, \mathrm{e} \in E_{T-1} \tag{10}$$

$$\sum_{v,l} \mathrm{q}_{\mathrm{plhve}} = \sum_{v,c} \mathrm{q}_{\mathrm{phcve}} \quad \forall \mathrm{h}, p, \mathrm{e} \in E_{T-1} \tag{11}$$

$$\mathrm{y}_{\mathrm{iwe}} \leq \sum_{\beta} \theta_{\mathrm{w\beta e}} \quad \forall \mathrm{i}, \mathrm{w}, \mathrm{e} \in E_{T-1} \tag{12}$$

$$\mathrm{y}_{\mathrm{wie}} \leq \sum_{\beta} \theta_{\mathrm{w\beta e}} \quad \forall \mathrm{i}, \mathrm{w}, \mathrm{e} \in E_{T-1} \tag{13}$$

$$\mathrm{y}_{\mathrm{ile}} \leq \sum_{\sigma} \mathrm{x}_{\mathrm{l\sigma e}} \quad \forall \mathrm{i}, \mathrm{l}, \mathrm{e} \in E_{T-1} \tag{14}$$

$$\mathrm{y}_{\mathrm{lie}} \leq \sum_{\sigma} \mathrm{x}_{\mathrm{l\sigma e}} \quad \forall \mathrm{i}, \mathrm{l}, \mathrm{e} \in E_{T-1} \tag{15}$$

$$\mathrm{My}_{\mathrm{ije}} \geq \mathrm{q}_{\mathrm{kijve}} \quad \forall \mathrm{i}, \mathrm{j}, \mathrm{k}, \mathrm{v}, \mathrm{e} \in E_{T-1} \tag{16}$$

$$\mathrm{Mu}_{\mathrm{pcl}} \geq \mathrm{q}_{\mathrm{pljve}} \quad \forall \mathrm{p}, \mathrm{c}, \mathrm{l}, \mathrm{j}, \mathrm{v}, \mathrm{e} \in E_{T-1} \tag{17}$$

$$\sum_{v,l} \mathrm{q}_{\mathrm{mrjve}} \leq \mathrm{cs}_{\mathrm{mr}} \quad \forall \mathrm{r}, \mathrm{m}, \mathrm{j}, \mathrm{v}, \mathrm{e} \in E_{T-1} \tag{18}$$

Model 2

$$\sum_{\sigma} \alpha_{\mathrm{le\sigma}} \leq 1 \quad \forall l, \mathrm{e} \in E_{T-1} \tag{19}$$

$$\sum_{\beta} \partial_{we\beta} \leq 1 \quad \forall w, \mathrm{e} \in E_{T-1} \tag{20}$$

$$\sum_{j,p,v} \mathrm{q}_{\mathrm{pljve}} \leq \mathrm{CP}_{\mathrm{le}} \quad \forall \mathrm{l}, \mathrm{e} \in E_{T-1} \tag{21}$$

$$\sum_{v,s,m} \mathrm{q}_{\mathrm{mswve}} \leq \mathrm{AS}_{\mathrm{we}} \quad \forall \mathrm{w}, \mathrm{e} \in E_{T-1} \tag{22}$$

$$CP_{l0} = cp_l + \sum_{\sigma} cap_{\sigma}\, \alpha_{\mathrm{l0\sigma}} \quad \forall l \tag{23}$$

$$CP_{le} = CP_{la(e)} + \sum_{\sigma} cap_{\sigma}\, \alpha_{\mathrm{le\sigma}} \quad \forall l, \mathrm{e} \in E_{T-1} \setminus \{0\} \tag{24}$$

$$AS_{w0} = as_w + \sum_{\beta} cap_\beta \, \partial_{w0\beta} \qquad \forall w \tag{25}$$

$$AS_{we} = AS_{wa(e)} + \sum_{\beta} cap_\beta \, \partial_{we\beta} \qquad \forall w, \mathrm{e} \in E_{T-1} \backslash \{0\} \tag{26}$$

$$\sum_{\sigma} \mathrm{x}_{\mathrm{l}\sigma\mathrm{e}} \leq 1 \qquad \forall \mathrm{l}, \mathrm{e} \in E_{T-1} \tag{27}$$

$$\sum_{\theta} \theta_{\mathrm{w}\beta\mathrm{e}} \leq 1 \qquad \forall \mathrm{w}, \mathrm{e} \in E_{T-1} \tag{28}$$

$$CP_{le} \leq \sum_{\sigma} cap_\sigma \, \mathrm{x}_{\mathrm{l}\sigma\mathrm{e}} \qquad \forall l, \mathrm{e} \in E_{T-1} \tag{29}$$

$$AS_{we} \leq \sum_{\beta} cap_\beta \, \theta_{\mathrm{w}\beta\mathrm{e}} \qquad \forall w, \mathrm{e} \in E_{T-1} \tag{30}$$

$$y_{ije} d_{ij} \leq dist_{max} \qquad \forall i, j, \mathrm{e} \in E_{T-1} \tag{31}$$

Constraints (6) guarantee that all customer demands, for all products, are satisfied. Constraints (7) ensure that plants receive enough materials to produce the required quantity of products. Constraints (8), (9), (10) and (11) impose the conservation of flows in the entire supply chain. These flows can only be established between two open entities (constraints (12), (13), (14) and (15)). Constraints (16) impose that we only send goods through links that are open (M being an upper bound on the maximum possible quantity). Constraints (17) impose that we only produce a product in a plant previously selected for its production.

Constraints (19) and (20) guarantee that we only increase the capacity levels once in each plant or warehouse under each event. Constraints (21) and (22) guarantee that plants cannot produce more than the installed capacity. Constraints (23), (24), (25) and (26) are similar, and they define the level of capacity under an event, as the level of capacity under the antecedent (previous) event plus any occurring capacity expansion. Constraints (27) and (28) assure that once a new plant or warehouse has been opened, in the next period it will be open with the same or higher capacity. Constraints (29) and (30) guarantee that there is at most one level of capacity for each plant or warehouse under each event.

Together with the cost minimization objective function, constraints (29) and (30) guarantee that the appropriate level of capacity for each plant or warehouse under each event is defined.

Constraints (31) aim at guaranteeing that new facilities will be open sufficiently close to customer markets.

6.3. Experimental Evaluation

We have changed the numerical example used in Model 1 by adding a new plant, in order to test all the possibilities of the new models.

We have assumed the company has a supply chain with 2 suppliers (r), 3 customers (c), 1 advanced warehouse (w), 2 plants and 1 potential new plant (warehousing and production) (l), 2 potential locations for opening new advanced warehouses (h), 4 finished products (p), 3 main raw-materials (m) and 3 types of vehicles.

In this study we will have 3 types of events (3 different possibilities for the uncertainty factor behavior) that may occur at a given time period, with a specific probability associated. The set of 2 events in two successive time periods is a scenario. As previously referred, in this specific case, we will consider two time periods (3 instants), leading to a tree with 9 scenarios, 13 nodes and 12 arcs.

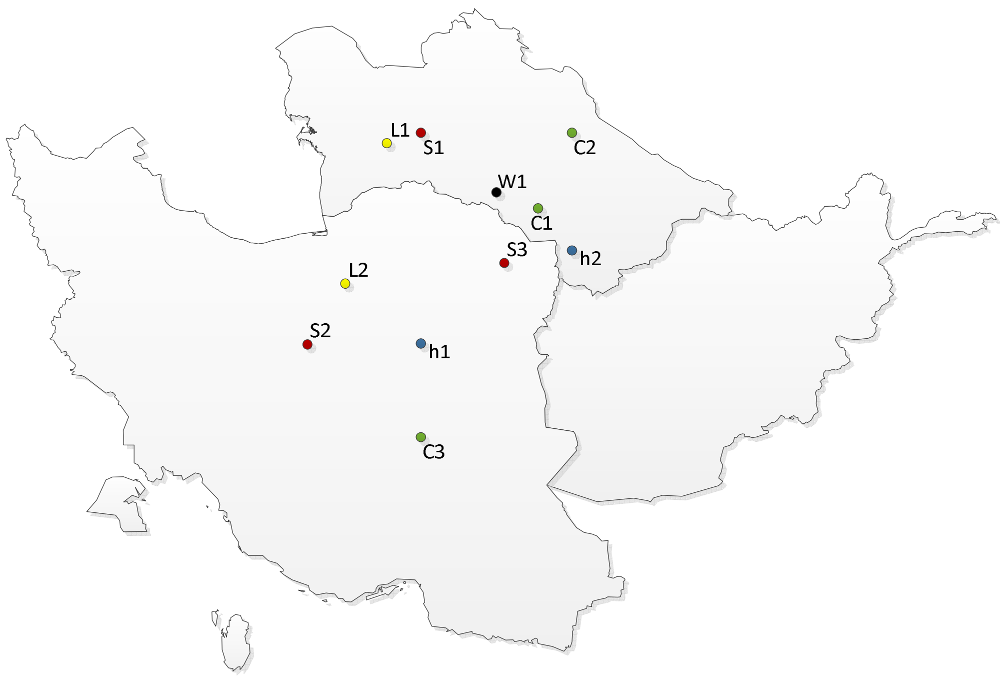


Figure 36: Supply Chain of Model 2 and Model 3

For the probabilities associated to each event and for the demand, we have used the same values presented in Model 1.

We have run a set of computational experiments on this example, with IBM ILOG CPLEX Optimizer Studio version 12.2, to study the impact of the uncertainty parameters.

To evaluate this model, we have only studied the behavior of the inflation rate, as uncertainty parameter, and its influence in the supply chain design. As in Model 1, we have considered 3 different situations to study the behavior of the model under uncertainty.

Table 10 shows the results obtained by running the model for the different situations.

Table 10: Results for the test instances

	Int. variables/ Cont. variables/ Constraints	Linear Relaxation	Iterations	Integrality gap[%]	Objective	CPU Time (sec.)
Situation 1	9852/	-0,1601	10952	0	0,042	213
Situation 2	6592/	-0,0495	11568	0	0,152	568
Situation 3	10125	-0,0842	16375	0	0,78	245

All computations were run using the Branch and Bound of IBM ILOG CPLEX Optimizer Studio version 12.2 on a PC Intel® Core™2Duo CPU U9400 1.4GHz and 3 GB RAM under Windows 7 Professional SP1. A normalization of the objective function was performed for all the tested cases.

We have run the model several times, with different inputs, in order to test its practical performance. The results obtained were always plausible from a practical point of view. To allow a solution assessment and validation by the users, the solutions for each situation were partially represented in a graphical way (Figure 37, 39 and 40) with numerical information on the links enabling the analysis of all values, from costs to capacities and requirements.

In the obtained solutions, some scenarios use warehouses, as already expected due to the consideration of a maximum distance between company facilities and markets. The use of warehouses has a significant cost, but not using an existing warehouse and exceeding the maximum allowed distance, has a penalty. This aspect was considered because when the company is far away from the markets, the probability of losing a client increases. The automotive industry is known to work under Just-in-Time rules, and therefore OEMs need to have suppliers physically close. In general the maximum allowed distance corresponds to a day in transit, using trucks and respecting the prevailing legislation.

In Table 11 we summarize the main costs resulting from the application of Model 2. Situation 2 is the worst (more expensive). In this situation the costs were 9.872.500€ for transportation, a value much higher than in Model 1 because most of the operations are in Country 1, with a minimum number of operations in Country 2. The inflation rate associated with the maximum distance requirement causes a deep change in the results. After the first period, the evolution of the supply chain structure led to the need to open a new warehouse in Country 1 (H2). We have also observed, in events 2 and 3, that the raw-materials had only one source, Supplier 1, because the savings in raw-materials are higher than the increase in transportation costs.

Situation 2 has a cost of 8.125 € for establishing links between two entities, 39.126 € for raw-materials and 1.020 € for production. The warehousing cost is 871 € and the fixed cost with existent plants is 23.200 €. The investment in new infrastructures is 11.080 € due to the new warehouse. The objective functions related with new locations (developed to minimize current and future costs with new warehouses) take the value 4 in what concerns easiness of easiness of doing business and labor costs.

Similarly to what had happened with Model 1, the supply chain structure changes with the situation, due to the inflation rate, to the maximum distance constraint, and to the probabilities associated with the costs of production in each plant and with the total costs of the transportation network. For some events plant L1 is deactivated, because the costs in Country 2 are most favorable.

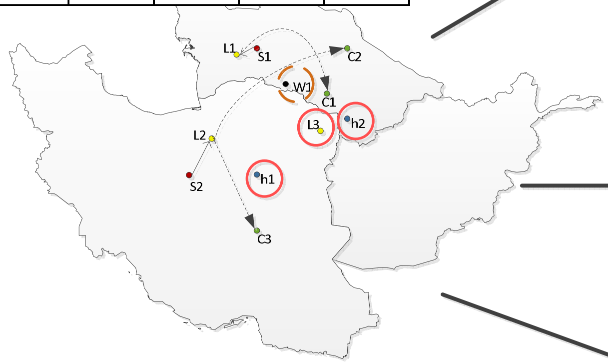
The behavior observed in Situation 1 is similar to that of Situation 2. But in Situation 3 we had different results. Plant L1 is not used because in the first period the whole production is allocated to plant L2, due to the lower costs and to the fact that it is not allowed to change after production has started. But this first decision involves an increase in capacity of plant L2 in the following periods. Therefore most of the operation takes place in Country 2, but in the second period, under events 2 and 3, the situation is different. Warehouses H1 and H2 are open to help plant L2 in sending the products for customers in Country 1 and thus decreasing the penalty for exceeding the maximum distance constraint.

This is just a small example used to illustrate part of the company's real operation, but all the results have been discussed and validated with the people involved in the project. Changing the values of probabilities for each scenario was also helpful to allow the users to assess the impact of uncertainty in terms of the different objectives. With this model we have been able to improve the quality and reliability of decisions, considering the change of capacities as well as the possibility of opening new infrastructures.

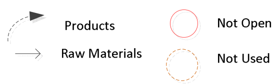
Table 11: Costs of each situation – Model 2

Objective functions	**Situation 1**	**Situation 2**	**Situation 3**
Transportation	8.964.500	9.872.500	9.799.700
Links	7.189	8.125	8.125
Raw-Materials	42.128	39.126	36.125
Production	1995,7	1020	1989
Plants	20.240	23.200	20.800
Warehouses	625	871,75	795,38
Increase Capacity	7253	15400	16640
New Infrastructures	10.201	11.080	11.220
Cost (f1)	9.054.131,7	9.971.322,75	9.895.397,38
Easiness of Doing Business (f2)	4	4	6
Labor Costs (f3)	4	4	12

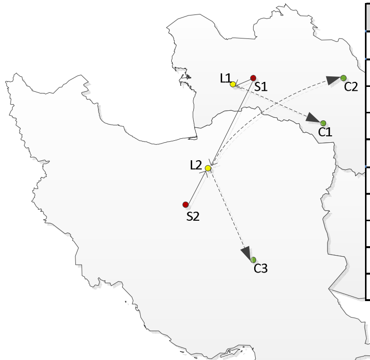
k	i	j	v	e	Value
PB_C1	L1	C1	V3	e0	100
PC_C2	L2	C2	V2	e0	70
PD_C3	L2	C3	V1	e0	200
RM1	S2	L2	V3	e0	160
RM2	S2	L2	V1	e0	70
RM2	S1	L1	V2	e0	60
RM3	S2	L2	V3	e0	169
RM3	S1	L1	V3	e0	80



Event 0

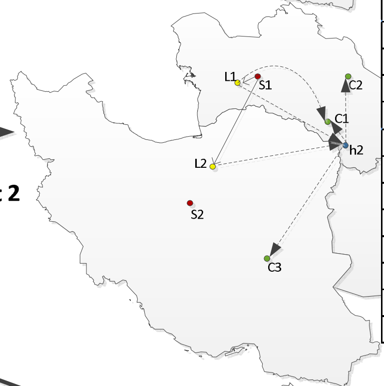


Event 1



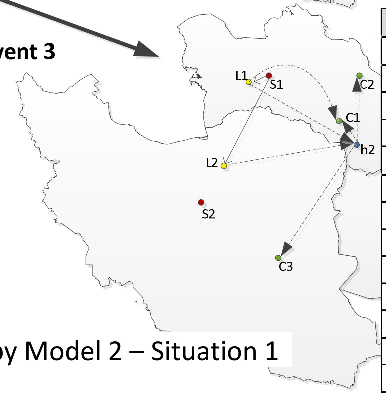
k	i	j	v	e	Value
PA_C1	L1	C1	V3	e1	120
PB_C1	L1	C1	V1	e1	75
PC_C2	L2	C2	V2	e1	70
PD_C3	L2	C3	V3	e1	200
RM1	S2	L2	V1	e1	160
RM1	S1	L1	V1	e1	120
RM2	S1	L1	V1	e1	129
RM2	S2	L2	V2	e1	70
RM3	S2	L2	V3	e1	169
RM3	S1	L1	V1	e1	60

Event 2



k	i	j	v	e	Value
PA_C1	L1	C1	V1	e2	120
PB_C1	L1	H2	V3	e2	75
PB_C1	H2	C1	V1	e2	75
PC_C2	L2	H2	V3	e2	70
PC_C2	H2	C2	V1	e2	70
PD_C3	L2	H2	V3	e2	200
PD_C3	H2	C3	V2	e2	200
RM1	S1	L2	V1	e2	160
RM1	S1	L1	V1	e2	120
RM2	S1	L1	V1	e2	129
RM2	S1	L2	V1	e2	70
RM3	S1	L1	V1	e2	60
RM3	S1	L2	V1	e2	169

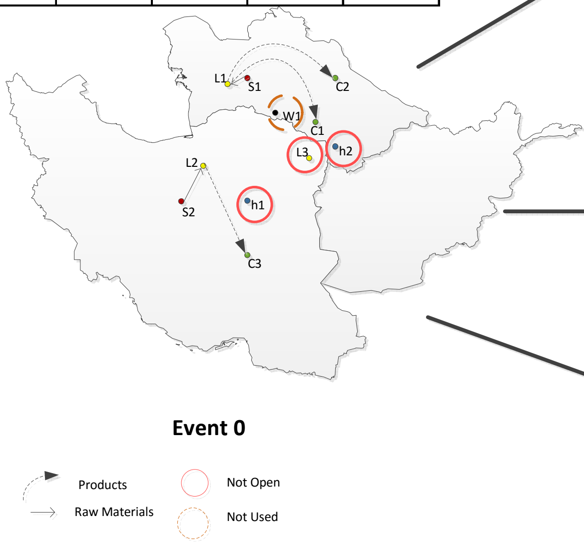
Event 3



k	i	j	v	e	Value
PA_C1	L1	C1	V1	e3	120
PB_C1	L1	H2	V3	e3	75
PB_C1	H2	C1	V3	e3	75
PC_C2	L2	H2	V2	e3	70
PC_C2	H2	C2	V3	e3	70
PD_C3	L2	H2	V3	e3	200
PD_C3	H2	C3	V1	e3	200
RM1	S1	L2	V1	e3	160
RM1	S1	L1	V1	e3	120
RM2	S1	L1	V1	e3	129
RM2	S1	L2	V1	e3	70
RM3	S1	L1	V1	e3	60
RM3	S1	L2	V1	e3	169

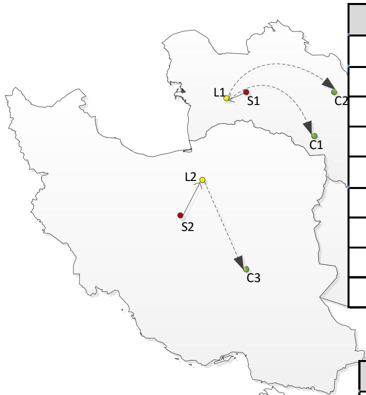
Figure 37: Results obtained by Model 2 – Situation 1

k	i	j	v	e	Value
PB_C1	L1	C1	V1	e0	100
PC_C2	L1	C2	V2	e0	70
PD_C3	L2	C3	V2	e0	200
RM1	S2	L2	V2	e0	160
RM2	S1	L1	V3	e0	130
RM3	S1	L1	V3	e0	129
RM3	S2	L2	V1	e0	120



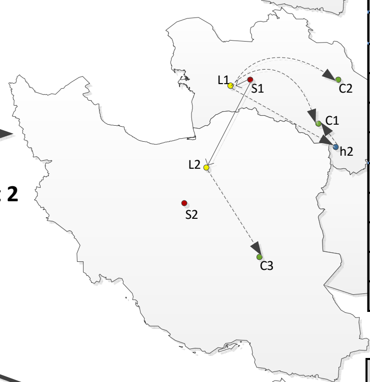
Event 0

Event 1



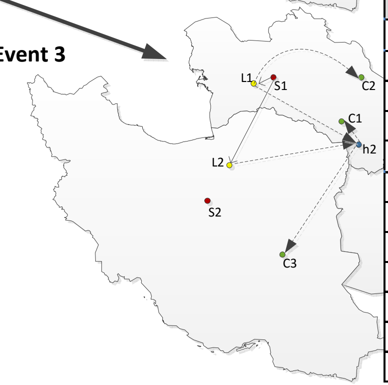
k	i	j	v	e	Value
PA_C1	L1	C1	V3	e1	120
PB_C1	L1	C1	V1	e1	75
PC_C2	L1	C2	V3	e1	70
PD_C3	L2	C3	V3	e1	200
RM1	S2	L2	V1	e1	160
RM1	S1	L1	V3	e1	120
RM2	S1	L1	V3	e1	199
RM3	S2	L2	V1	e1	120
RM3	S1	L1	V2	e1	109

Event 2



k	i	j	v	e	Value
PA_C1	L1	H2	V2	e2	120
PA_C1	H2	C1	V2	e2	120
PB_C1	L1	C1	V3	e2	75
PC_C2	L1	C2	V2	e2	70
PD_C3	L2	C3	V2	e2	200
RM1	S1	L2	V1	e2	160
RM1	S1	L1	V1	e2	120
RM2	S1	L1	V1	e2	199
RM3	S1	L2	V1	e2	120
RM3	S1	L1	V1	e2	109

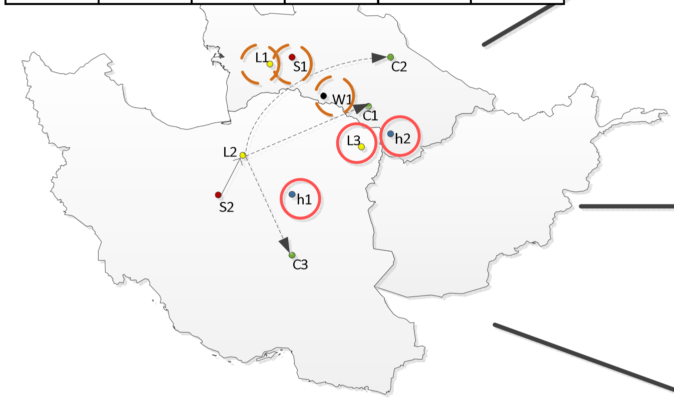
Event 3



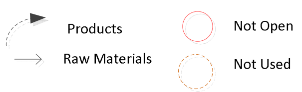
k	i	j	v	e	Value
PA_C1	L1	H2	V1	e3	120
PA_C1	H2	C1	V3	e3	120
PB_C1	L1	H2	V2	e3	75
PB_C1	H2	C1	V3	e3	75
PC_C2	L1	C2	V1	e3	70
PD_C3	L2	H2	V1	e3	200
PD_C3	H2	C3	V3	e3	200
RM1	S1	L2	V1	e3	160
RM1	S1	L1	V1	e3	120
RM2	S1	L1	V1	e3	199
RM3	S1	L2	V1	e3	120
RM3	S1	L1	V1	e3	109

Figure 38: Results obtained by Model 2 – Situation 2

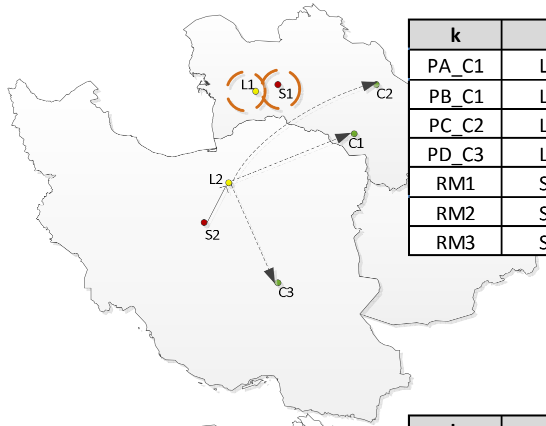
k	i	j	v	e	Value
PB_C1	L2	C1	V2	e0	100
PC_C2	L2	C2	V3	e0	70
PD_C3	L2	C3	V2	e0	200
RM1	S2	L2	V3	e0	160
RM2	S2	L2	V2	e0	130
RM3	S2	L2	V2	e0	249



Event 0

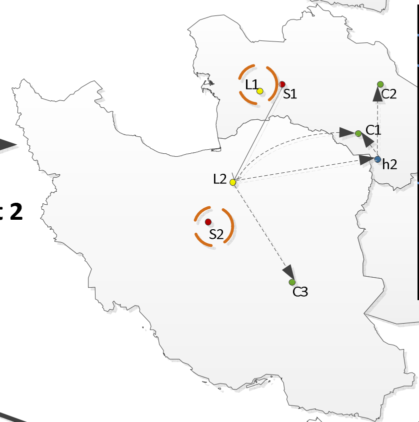


Event 1



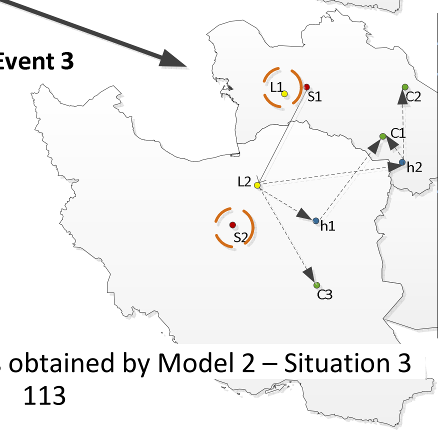
k	i	j	v	e	Value
PA_C1	L2	C1	V1	e1	120
PB_C1	L2	C1	V3	e1	75
PC_C2	L2	C2	V3	e1	70
PD_C3	L2	C3	V3	e1	200
RM1	S2	L2	V3	e1	280
RM2	S2	L2	V3	e1	199
RM3	S2	L2	V1	e1	229

Event 2



k	i	j	v	e	Value
PA_C1	L2	H2	V1	e2	120
PA_C1	H2	C1	V3	e2	120
PB_C1	L2	C1	V2	e2	75
PC_C2	L2	H2	V1	e2	70
PC_C2	H2	C2	V3	e2	70
PD_C3	L2	C3	V1	e2	200
RM1	S1	L2	V1	e2	280
RM2	S1	L2	V1	e2	199
RM3	S1	L2	V1	e2	229

Event 3



k	i	j	v	e	Value
PA_C1	L2	H2	V1	e3	120
PA_C1	H2	C1	V1	e3	120
PB_C1	L2	H1	V3	e3	75
PB_C1	H1	C1	V3	e3	75
PC_C2	L2	H2	V3	e3	70
PC_C2	H2	C2	V3	e3	70
PD_C3	L2	C3	V3	e3	200
RM1	S1	L2	V1	e3	280
RM2	S1	L2	V1	e3	199
RM3	S1	L2	V1	e3	229

Figure 39: Results obtained by Model 2 – Situation 3

6.3.1. Model 3

With Model 3 we have tested different evolutions of the uncertainty parameters. Although we have run several combinations of the possible behaviors, here we only present the most relevant of these combinations. The combinations are presented in Table 11.

Table 12: Evolution of Brent uncertainty parameter

Uncertainty	Inflation	Brent	Scenario
Zone1	Situation1	↑	**1’**
Zone2		=	
Zone1	Situation2	↓	**2’**
Zone2		↓	
Zone1	Situation3	=	**3’**
Zone2		↑	

The evolution of *brent* costs was obtained from publically available studies and it is expressed in percentage of the cost increase. The three studied situations take into account the current values in each country, increased by 15% and decreased by 10% (these values reflect the recent evolutions of the market).

The *Vulnerability Parameter* is computed through a ranking procedure developed during this project (ranging from 0 to 5). This parameter was computed for each country, based on data related to social conditions, the political situation, the probability of occurrence of a natural disaster as well as its potential destructive impacts (hurricanes, earthquakes, climacteric characteristics), the economic situation (stable or crisis) and the security level (likelihood of terrorism and sabotage actions).

All computations were run using the Branch and Bound of IBM ILOG CPLEX Optimizer Studio version 12.2 on a PC Intel® Core™2Duo CPU U9400 1.4GHz and 3 GB RAM under Windows 7 Professional SP1. A normalization of the objective function was performed for all the tested cases.

Table 13: Results for the test scenarios

	Int. variables/ Cont. variables/ Constraints	**Linear Relaxation**	**Iterations**	**Integrality gap[%]**	**Objective**	**CPU Time (sec.)**
Scenario 1	1933/	0,3401	10084	1,32	0,185	534
Scenario 2	1645/	0,2822	11853	1,05	0,130	894
Scenario 3	3140	0,3096	10299	0,94	0,610	659

As done previously, we have run the model several times with different inputs, in order to test its practical performance. The results obtained have always been considered plausible in a practical perspective. To allow a solution assessment and validation by the users, the solutions for the 3 situations have been partially represented in a graphical way (Figure 38), thus supporting the analysis of all values, from costs to capacities and requirements. Situation 3, although with different values, led to the same supply chain structure.

In the obtained solutions, warehouses have not been used. In an initial phase this behavior was not expected, but after analyzing all values, we could understand it, as a way to avoid risks associated with the vulnerability uncertainty parameter. The model favored minimum risk against an increase in costs and penalties.

Decreasing the vulnerability of the supply chain led to an increase of the capacity in plants, namely in plant L1. It should also be noted that trying to avoid crossing borders. The vulnerability adds a value for each open location at which the decisions will tend to have a few locations and areas of reduced vulnerability.

In Table 13 we summarize the main costs for Model 3. Situation 3 is the worst (more expensive). In this case the costs were 8.100.659 € for transportation, a value much near that in Model 2. Similarly to Model 2, we have also observed in Events 2 and 3 that the raw-materials had only one source, Supplier 1, because the savings in the costs of raw-materials are higher than the increase in transportation costs.

Situation3 has a cost of 9.571 € for establishing links between two entities, 36.304 € for raw-materials and 1.359 € for production. The fixed cost with the existing plant is 20.800 €. No investments in new infrastructures have been done, but capacity increase represented a cost of 11.000 €.

The behavior observed in Situation 3 is similar to Situation 2 and 1, with the same supply chain structure but with a little fluctuation in costs. We could observe a preference in increasing capacity against opening new infrastructures. The model under Events 2 and 3 did not select Supplier2. As a way to avoid the increased vulnerability of using different countries.

Table 14: Costs of each situation – Model 3

Objective Functions	Scenario 1	Scenario 2	Scenario 3
Transportation	7.588.203	7.521.334	8.100.659
Links	7.189	8.125	9.571
Raw-Materials	39.519	39.126	36.304
Production	1.995,7	1020	1359,4
Plants	20.240	23.200	20800
Warehouses	0	0	0
Increase Capacity	10.098	11.000	11.000
New Infrastructures	0	0	0
Cost (f1)	7.667.244,7	7.603.805	8.179.693,4
Easiness of Doing Business (f2)	0	0	0
Labor Costs (f3)	0	0	0

As in previous test we used the same a small example to illustrate a part of the reality of this industry. The results and conclusions were discussed and validated with the people involved in the project. Changing the values of probabilities for each scenario was also helpful to allow the users to assess the impact of uncertainty in the different objectives. With this model we improve the quality and reliability of the decisions considering the possibility of changing capacities, opening new infrastructures, the future evolution of *brent* costs, as well as the supply chain vulnerability.

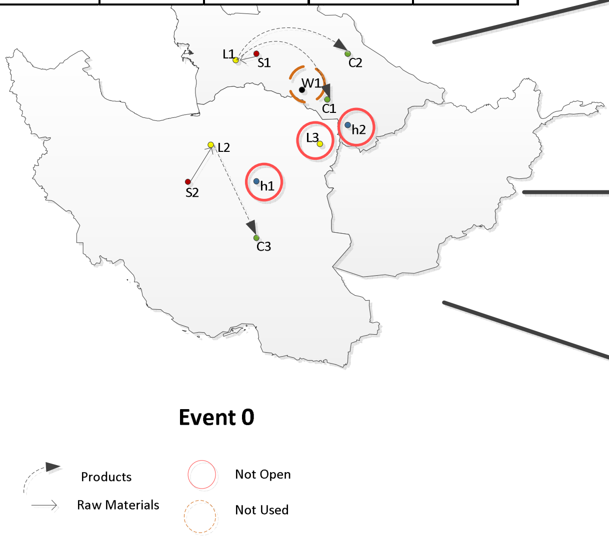
In the weights assigned to each component of the objective function, vulnerability takes the value of 10% (80% for costs, 5% for easiness of doing business and 5% for labor costs). After several runs, we noted such dramatically affect the behavior of the model that avoids exposure of the supply chain to the risk. We have noted a quite significant effect on the supply chain risk exposure.

Eliminating the parameter corresponding to the vulnerability and moving its weight to the costs component, the existing warehouse becomes part of the solution and the total costs decrease 20,5%. This situation can be observed in Figure 40.

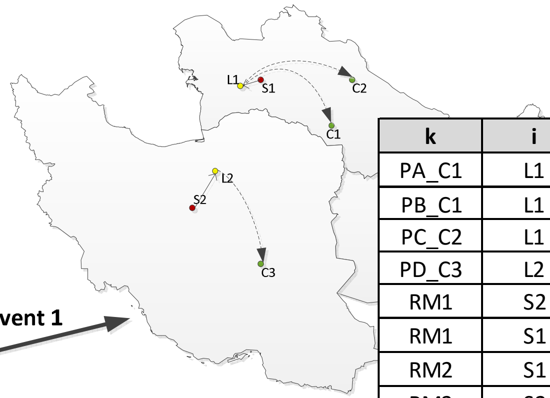
We have also concluded that the vulnerability try to reduce the number of connections, for example eliminating warehouses in the supply chain. The model chooses direct links (from suppliers to plants, and from plants to customers) since the cost penalty for exceeding the maximum distance pays face of decreased exposure to risk.

We have also concluded that maximum vulnerability leads to a reduced number of connections and the elimination of warehouses. The model increases the number of direct links since the cost penalty for exceeding the maximum distance compensates the decrease in exposure to risk.

k	i	j	v	e	Value
PB_C1	L1	C1	V1	e0	100
PC_C2	L1	C2	V3	e0	70
PD_C3	L2	C3	V1	e0	200
RM1	S2	L2	V3	e0	160
RM2	S1	L1	V2	e0	130
RM3	S1	L1	V3	e0	129
RM3	S2	L2	V1	e0	120

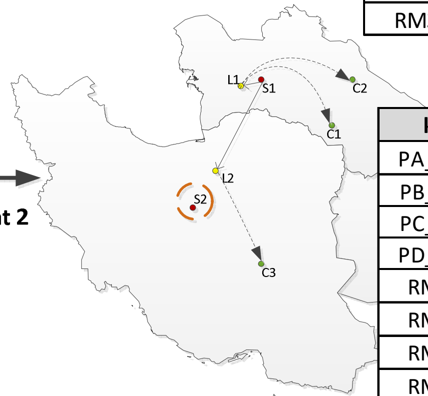


Event 1



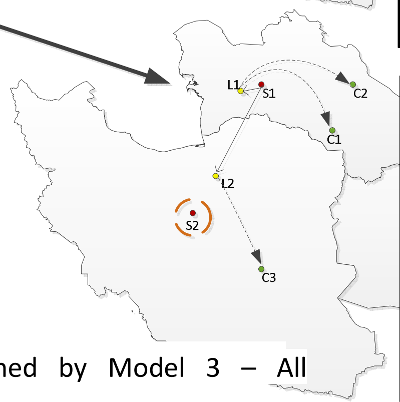
k	i	j	v	e	Value
PA_C1	L1	C1	V1	e1	120
PB_C1	L1	C1	V3	e1	75
PC_C2	L1	C2	V2	e1	70
PD_C3	L2	C3	V1	e1	200
RM1	S2	L2	V2	e1	160
RM1	S1	L1	V3	e1	120
RM2	S1	L1	V1	e1	199
RM3	S2	L2	V2	e1	120
RM3	S1	L1	V3	e1	109

Event 2



k	i	j	v	e	Value
PA_C1	L1	C1	V3	e2	120
PB_C1	L1	C1	V2	e2	75
PC_C2	L1	C2	V2	e2	70
PD_C3	L2	C3	V1	e2	200
RM1	S1	L2	V1	e2	160
RM1	S1	L1	V1	e2	120
RM2	S1	L1	V1	e2	199
RM3	S1	L2	V1	e2	120
RM3	S1	L1	V1	e2	109

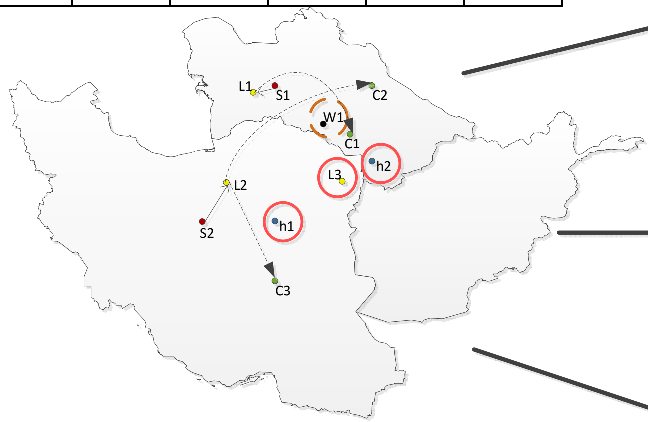
Event 3



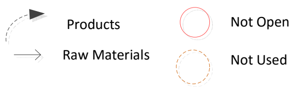
k	i	j	v	e	Value
PA_C1	L1	C1	V3	e3	120
PB_C1	L1	C1	V3	e3	75
PC_C2	L1	C2	V1	e3	70
PD_C3	L2	C3	V2	e3	200
RM1	S1	L2	V1	e3	160
RM1	S1	L1	V1	e3	120
RM2	S1	L1	V1	e3	199
RM3	S1	L2	V1	e3	120
RM3	S1	L1	V1	e3	109

Figure 40: Results obtained by Model 3 – All

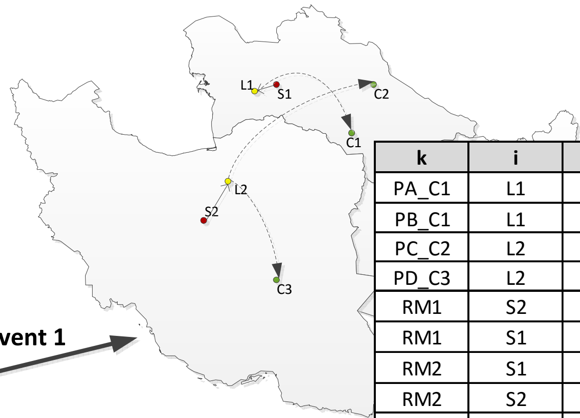
k	i	j	v	e	Value
PB_C1	L1	C1	V1	e0	100
PC_C2	L2	C2	V1	e0	70
PD_C3	L2	C3	V1	e0	200
RM1	S2	L2	V3	e0	160
RM2	S2	L2	V3	e0	70
RM2	S1	L1	V2	e0	60
RM3	S2	L2	V2	e0	169
RM3	S1	L1	V3	e0	80



Event 0

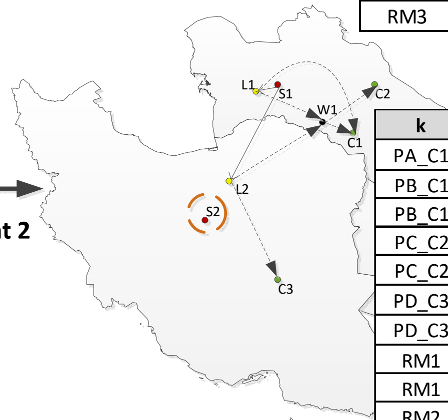


Event 1



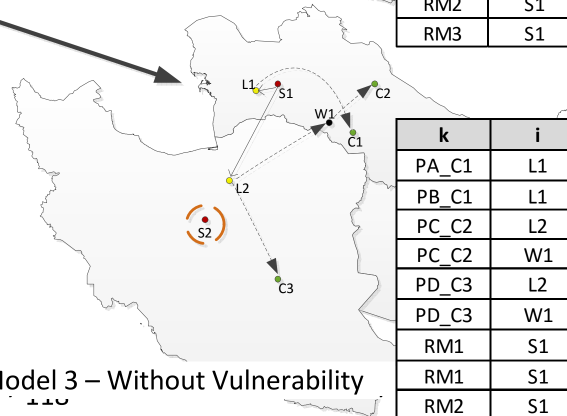
k	i	j	v	e	Value
PA_C1	L1	C1	V1	e1	120
PB_C1	L1	C1	V3	e1	75
PC_C2	L2	C2	V3	e1	70
PD_C3	L2	C3	V2	e1	200
RM1	S2	L2	V3	e1	160
RM1	S1	L1	V2	e1	120
RM2	S1	L1	V1	e1	129
RM2	S2	L2	V3	e1	70
RM3	S1	L1	V3	e1	60
RM3	S2	L2	V1	e1	169

Event 2



k	i	j	v	e	Value
PA_C1	L1	C1	V3	e2	120
PB_C1	L1	W1	V3	e2	75
PB_C1	W1	C1	V1	e2	75
PC_C2	L2	W1	V2	e2	70
PC_C2	W1	C2	V2	e2	70
PD_C3	L2	W1	V2	e2	200
PD_C3	W1	C3	V2	e2	200
RM1	S1	L2	V1	e2	160
RM1	S1	L1	V1	e2	120
RM2	S1	L1	V1	e2	129
RM3	S1	L2	V1	e2	169

Event 3



k	i	j	v	e	Value
PA_C1	L1	C1	V3	e3	120
PB_C1	L1	C1	V3	e3	75
PC_C2	L2	W1	V2	e3	70
PC_C2	W1	C2	V1	e3	70
PD_C3	L2	W1	V2	e3	200
PD_C3	W1	C3	V1	e3	200
RM1	S1	L2	V1	e3	160
RM1	S1	L1	V1	e3	120
RM2	S1	L1	V1	e3	129
RM3	S1	L2	V1	e3	169

Figure 41: Results obtained by Model 3 – Without Vulnerability

6.4. Case Study Application

In the scope of our collaboration with Simoldes, we have performed a final application of the models proposed in this chapter to a realistic instance based on the company's supply chain network.

After validation of the models with a small example, we have prepared the data collected from the case study, as well as some other relevant data published by public entities, to be used as input. Part of the data has already been presented in a map format in chapter 4, and that presentation is completed in Figure 41. The output of the optimization step was carefully analyzed, revealing to be aligned with network configuration recommendations that had resulted from an earlier analysis of the project team.

The company showed more interest in using only Model 2 in a first phase, and recognized the value of this new tool to structure and assess situations such as opening a new warehouse in a specific place, with implications in the flows of materials and the potential to reduce costs.

This report is very concise due to restrictions on the disclosure of information. For confidentiality reasons we can neither show the full studies nor present the collected and produced data.

All the costs related with warehouses, plants, raw-materials, production and transportation were provided by the company and used in the model.

In fact the results obtained are similar to the results from a previous analysis developed with Simoldes, that suggested to open the same warehouses, making the same allocation of production and setting up a similar configuration of the distribution network. The results reflect the importance of proximity to markets with a higher business interest for the company, lower costs, and the minimization of vulnerability (by avoiding some countries considered critical, such as Romania).

The greatest benefit recognized by the industrial partner was related to the easiness of analysis when using the tool developed in this project. However, the time required to test and assess alternative designs for a new infrastructure was also significantly reduced, thus improving the decision-making process. It is now possible to test different sets of frequent uncertainties in supply chains of the automobile industry, in a short time.

Another aspect valued by the users was the capability to anticipate the consequences of decisions in a long-term perspective, and to more consistently evaluate their impact.

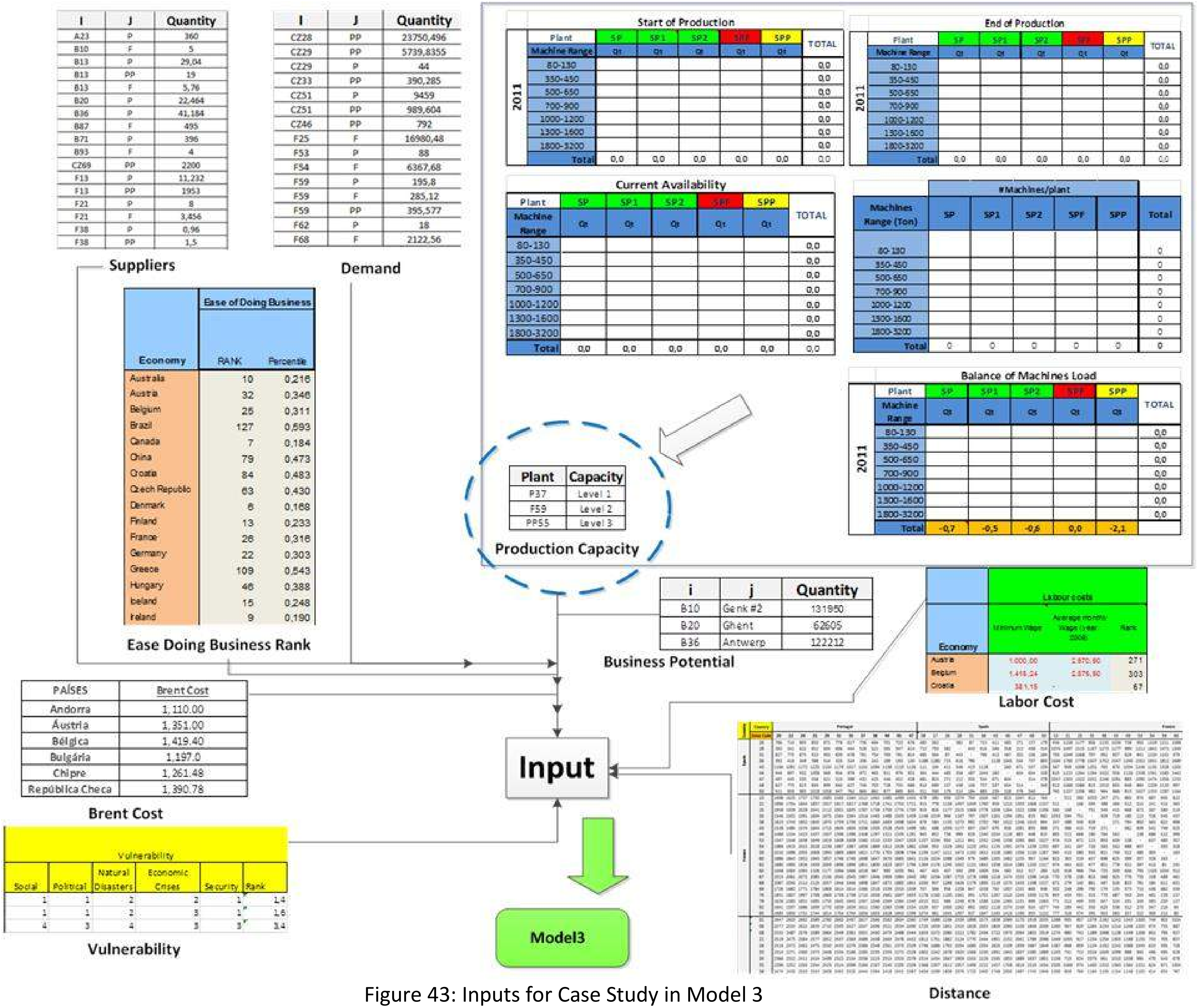


Figure 43: Inputs for Case Study in Model 3

6.5. Conclusions

In this work we have extended an initial model for supply chain design in the automotive industry, explicitly incorporating uncertainty. The proposed extensions improve the support to strategic-tactical decision-making, and increase the coverage of features relevant to real and practical environments.

These extensions clearly show the importance of considering unusual uncertainties, such as *vulnerability* or the evolution of *brent cost,* in this type of analysis. We have obtained significantly better results with the new versions of the model, thus fulfilling the objectives initially defined for this research.

Another important achievement of this project was the application of the model to a real case study, and its assessment and validation by our industrial partners.

7. Conclusions and further developments

7.1. Conclusions

In the current economic situation, with industry trying to recover from a deep contraction, the goals of this dissertation seem even to be more meaningful. Industrial organizations are setting their efforts more and more on the control and reduction of costs, not only as a way to address intensified competition, but also to support their recovery from the challenges posed by the current global economic and financial crisis. In recent years, companies have intensified their attention to the field of supply chain design, seeking to become more competitive in increasingly globalized environments. The global economic and financial crisis has further reinforced the importance of this field to industrial organizations.

In this work, a model for supply chain design in the automotive industry, explicitly incorporating uncertainty, has been developed. This stochastic model aims at supporting strategic-tactical decision-making, and covers a set of different features of real, practical environments, namely: multi-period planning horizons, multi-criteria assessment of policies, international issues such as exchange rates, and some major specific concerns of companies.

The extensions applied to the first model developed in this work reveal the importance, in this context, of considering uncertainties not usually addressed, such as vulnerability and the *brent* cost evolution. The results obtained with these model extensions are quite satisfactory, positively supporting the decision-making process. Moreover the obtained results were very useful in our real case study and have therefore been validated by our industrial partner.

Contributing to a better understanding of these issues has been the most general motivation for this doctoral project, taking also into account a strong motivation to develop research in an industrial environment, and guaranteeing a deep interaction between scientific and industrial activities.

Accordingly, the project has dealt with the need to:

- develop a model to support strategic and tactical decision-making;
- integrate risk management concerns, improving the reaction to uncertainties, dynamics and accidents (vulnerabilities);
- contribute to increasing the efficiency of supply chains.

In this work, a model for supply chain design in the automotive industry, dealing with uncertainty, has been developed. In particular, this stochastic model supports strategic-tactical decision-making. Moreover the model covers a set of different features of real, practical environments, namely: multi-periods planning horizons, multi-criteria assessment of policies, international issues such as exchange rates, and some major specific concerns of companies.

Moreover the integrated approaches we have developed can also be further used in support decision making in operations strategy planning, and also in understanding how the supply chain network should evolve in a long term horizon, in order to optimize the profitability of operations. For such purpose, these models have been designed based on the definition of scenarios for future evolution of supply, demand, transportation and other critical elements of the supply chain network.

The financial crisis has clearly shown the vulnerability of our global economy. The automotive is one of the most affected industrial sectors, facing a consistent decrease in the sales of vehicles and an increase of the prices of oil and steel, this clearly justifying to pursue research aligned with the concerns of industry and to develop tools to help in the recovery of markets.

One basic assumption to justify this research was that supply chain management can play a prominent role in improving the performance of this sector, by enhancing systems already in place or by designing and implementing new systems. In this industry, supply chain design strongly depends on the dynamics of markets that lead to high levels of uncertainty. This aspect has been often neglected in the literature.

The main objective of our work was therefore to fulfill this gap by proposing a model that explicitly considers the risk directly associated with uncertainty factors. The developed stochastic model takes into account the specific features of the global modern automotive supply chain and it aims at supporting strategic and tactical decision-making (design, investments and transportation network).

Our work also approaches two types of uncertainties – extreme and typical. Extreme uncertainties are related to strong disruptions of supply chains, that require a resilience capability of companies to recover. Typical uncertainties are less problematic when the supply chains have a risk management process implemented, supported by tools that provide the supply chain with the flexibility required to adapt quickly and efficiently to changes in the environment. Flexibility is improved by the capacity of adaptability, collaboration and visibility across the supply chain.

These were the main original contributions of this dissertation, fully validated by the application of the developed integrated models to some variants of the case study through an assessment of the results by the real decision-makers in the company.

The nature of the models and general approach developed in this work make naturally applicable in other companies and contexts, and hopefully easy to extend to other complex supply chains in other sectors.

7.2. Further developments

Decision making in Modern Supply Chains is critically challenged by industry and market dynamics and uncertainties. In an aggregate way, we have developed a model with impact in strategic-tactical decision-making, and covering a set of different features relevant to real and practical environments. In the near future, the developments of this work should focus on:

- considering the possibility of moving the production of products;
- integrating autonomous decision making and contracts with suppliers and customers, considering features such as Incoterms and penalties;
- analyzing the sources of flexibility that are present in this kind of networked infrastructures, and their value to deal with uncertainty.

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Annexes

I. Data of Model1

```
Suppliers = {S1 S2};

Customers = {C1, C2, C3};

Plants = {L1, L2};

Warehouses = {W1};

Potential = {H1, H2};

Vehicles = {V1, V2, V3};

Products = {PA_C1, PB_C1, PC_C2, PD_C3};

RawMaterials = {RM1, RM2, RM3};

Time = {0,1,2};

Event = {e0, e1, e2, e3, e4, e5, e6, e7, e8, e9 ,e10, e11, e12};

Distance = [50, 220, 225, 100, 125, 310, 252, 150, 250, 360,150, 225,265, 130,
245, 300,220, 250, 380, 260, 350, 220, 150, 225, 265, 245, 130, 300,60, 125,
340, 240, 340, 125, 330, 430, 325];

CB = [4, 8];

CL = [1, 5];

Demand = [0,120,120,100,75,0,70,70,70,200,200,200];

CostKM = [1.3, 1.3, 0.9, 0.9, 1.3,0.9,1.3, 1.3, 0.9, 0.9, 1.3,1.3, 0.9,0.9,1.3,
1.3, 1.3, 1.3, 1.3, 0.9,0.9,0.9,1.3, 0.9, 1.3,1.3,0.9,0.9, 1.3,1.3,1.3,
0.9,0.9,0.9,1.3,1.3,1.3, 1.3, 1.3, 0.9, 0.9, 1.3,0.9,1.3, 1.3, 0.9, 0.9,
1.3,1.3, 0.9,0.9,1.3, 1.3, 1.3, 1.3, 1.3, 0.9,0.9,0.9,1.3,0.9, 1.3,1.3,0.9,0.9,
1.3,1.3,1.3, 0.9,0.9,0.9,1.3,1.3,1.3, 1.3, 1.3, 0.9, 0.9, 1.3,0.9,1.3, 1.3, 0.9,
0.9, 1.3,1.3, 0.9,0.9,1.3, 1.3, 1.3, 1.3, 1.3, 0.9,0.9,0.9,1.3, 0.9,
1.3,1.3,0.9,0.9, 1.3,1.3,1.3, 0.9,0.9,0.9,1.3,1.3,1.3];

CO =[100, 300, 300, 100, 100, 300, 300, 100, 300, 300, 100, 300, 300, 100, 100,
300, 100, 100, 300, 300, 300, 100, 100, 300, 300, 100, 100, 300, 100, 100, 300,
300, 300, 100, 100, 100, 300];

FC = [50];

FP = [83, 51];

VC = [2];

VP = [1.8, 1.4];

VCH = [0.8];

VPH = [0.5, 0.7];

AS = [520, 850, 750, 1000, 750, 1500, 500];

CS = [500, 200, 400, 0, 700, 500];



Cp = [450, 850];

RM = [0, 120, 120, 0, 0, 0,0, 0, 0, 160, 160, 200, 0, 84, 84, 60, 45, 0,70, 70,
70, 0, 0, 0,  0, 0, 0, 80, 60, 0,49, 49, 49, 120, 120, 120];
```

```
CV = [1, 0.95, 9, 9.6, 0.15, 0.12];

CPP = [0.8, 0.7, 0.6, 0.6, 0.8, 0.5, 0.6, 0.5];

TC = [90 100 210];

PB =[1,0.5,0.3,0.2, 0.5,0.3,0.2, 0.3, 0.5,0.2,0.3,0.2,0.5];

IR1 = [1.029, 0.97, 1.029, 1.029, 0.97,0.97, 1.029,       1.01, 1.03, 1.01,
1.01, 1.03,1.03, 1.01,1.01, 1.03, 1.01, 1.01, 1.03,1.03, 1.01,1.01, 1.03, 1.01,
1.01, 1.03,1.03, 1.01,1.01, 1.01, 1.01, 1.01, 1.01,1.01, 1.01,1.01, 1.01, 1.01,
1.01, 1.01,1.01, 1.01,1.01, 1.01, 1.01, 1.01, 1.01,1.01, 1.01,1.01, 1.01, 1.01,
1.01, 1.01,1.01, 1.01,1.01, 1.01, 1.01, 1.01, 1.01,1.01, 1.01,1.01, 1.01, 1.01,
1.01, 1.01,1.01, 1.01,1.01, 1.01, 1.01, 1.01, 1.01,1.01, 1.01,1.01, 1.01, 1.01,
1.01, 1.01,1.01, 1.01,1.01, 1.01, 1.01, 1.01, 1.01,1.01, 1.01];

IR2 = [1, 1, 1, 1, 1,1, 1,1, 1, 1, 1, 1,1, 1,1, 1, 1, 1, 1,1, 1,1, 1, 1, 1, 1,1,
1,1, 1, 1, 1, 1,1, 1,1, 1, 1, 1, 1,1, 1,1, 1, 1, 1, 1,1, 1,1, 1, 1, 1, 1,1, 1,
1, 1, 1, 1, 1,1, 1,1, 1, 1, 1, 1,1, 1,1, 1, 1, 1, 1,1, 1, 1, 1, 1, 1, 1,1, 1,1,
1, 1, 1, 1,1, 1];

IR3 = [1.4, 0.8, 1.4, 1.4, 0.8,0.8, 1.4, 1.4, 0.8, 1.4, 1.4, 0.8,0.8, 1.4,1.4,
0.8, 1.4, 1.4, 0.8,0.8, 1.4, 1.4, 0.8, 1.4, 1.4, 0.8,0.8, 1.4, 1.4, 0.8, 1.4,
1.4, 0.8,0.8, 1.4, 1.4, 0.8, 1.4, 1.4, 0.8,0.8, 1.4, 1.4, 0.8, 1.4, 1.4,
0.8,0.8, 1.4, 1.4, 0.8, 1.4, 1.4, 0.8,0.8, 1.4, 1.4, 0.8, 1.4, 1.4, 0.8,0.8,
1.4, 1.4, 0.8, 1.4, 1.4, 0.8,0.8, 1.4, 1.4, 0.8, 1.4, 1.4, 0.8,0.8, 1.4, 1.4,
0.8, 1.4, 1.4, 0.8,0.8, 1.4, 1.4, 0.8, 1.4, 1.4, 0.8,0.8, 1.4];

IR = [0.8, 1.4, 0.8, 0.8, 1.4,1.4, 0.8, 0.8, 1.4, 0.8, 0.8, 1.4,1.4, 0.8,0.8,
1.4, 0.8, 0.8, 1.4,1.4, 0.8 0.8, 1.4, 0.8, 0.8, 1.4,1.4, 0.80.8, 1.4, 0.8, 0.8,
1.4,1.4, 0.8,0.8, 1.4, 0.8, 0.8, 1.4,1.4, 0.8,0.8, 1.4, 0.8, 0.8, 1.4,1.4, 0.8,
0.8, 1.4, 0.8, 0.8, 1.4,1.4, 0.8,0.8, 1.4, 0.8, 0.8, 1.4,1.4, 0.8,0.8, 1.4, 0.8,
0.8, 1.4,1.4, 0.8,0.8, 1.4, 0.8, 0.8, 1.4,1.4, 0.8,0.8, 1.4, 0.8, 0.8, 1.4,1.4,
0.8,0.8, 1.4, 0.8, 0.8, 1.4,1.4, 0.8];
```

II. Data of Model 2

```
Suppliers = {S1 S2};

Customers = {C1, C2, C3};

PlantsActual = {L1, L2};

PlantsPotential = {L3};

WarehousesActual = {W1};

WarehousesPotential = {H1, H2};

Vehicles = {V1, V2, V3};

Products = {PA_C1, PB_C1, PC_C2, PD_C3};

RawMaterials = {RM1, RM2, RM3};

Time = {0,1,2};

Event = {e0, e1, e2, e3, e4, e5, e6, e7, e8, e9 ,e10, e11, e12};

Distance = [50, 220, 220, 255, 100, 295, 125, 252, 250, 310, 150, 360, 150, 225,
105, 265, 130, 165, 245, 300, 75,220, 250, 380, 260, 350, 220, 85, 195, 250,
150, 265, 245, 225, 130, 300, 105, 165, 75, 60, 125, 340, 240, 340, 125, 330,
430, 325];

CB = [4,4, 8];

CL = [1, 1,5];

Demand = [0,120,120,100,75,0,70,70,70,200,200,250];

CostKM = [0.9, 1.3, 1.3,1.3,0.9,0.9,0.9, 1.3, 0.9, 1.3, 0.9, 1.3, 0.9, 1.3, 1.3,
1.3, 0.9, 0.9, 0.9, 1.3, 1.3,0.9,0.9,1.3,1.3,1.3,0.9,1.3,1.3,0.9, 0.9, 1.3, 0.9,
1.3, 0.9, 1.3, 1.3, 0.9, 1.3,0.9, 0.9, 1.3, 1.3, 1.3, 0.9,0.9, 0.9,1.3,0.9, 1.3,
```

```
1.3,1.3,0.9,0.9,0.9, 1.3, 0.9, 1.3, 0.9, 1.3,0.9, 1.3, 1.3, 1.3, 0.9, 0.9, 0.9,
1.3, 1.3,0.9,0.9,1.3,1.3,1.3,0.9,1.3,1.3,0.9,0.9, 1.3, 0.9, 1.3, 0.9, 1.3, 1.3,
0.9, 1.3,0.9, 0.9, 1.3, 1.3, 1.3, 0.9,0.9, 0.9,1.3,0.9, 1.3, 1.3,1.3,0.9,0.9,
0.9, 1.3, 0.9, 1.3, 0.9, 1.3,0.9, 1.3, 1.3, 1.3, 0.9, 0.9, 0.9, 1.3, 1.3,0.9,
0.9,1.3,1.3,1.3,0.9,1.3,1.3,0.9, 0.9, 1.3, 0.9, 1.3, 0.9, 1.3, 1.3, 0.9, 1.3,
0.9, 0.9, 1.3, 1.3, 1.3, 0.9,0.9, 0.9,1.3];

CO =[100, 300, 300,300,100,100,100, 300, 100, 300, 100, 300,100, 300, 300, 300,
100, 100, 100, 300, 300,100,100,300,300,300,100,300,300,100,100, 300, 100, 300,
100, 300, 300, 100, 300,100, 100, 300, 300, 300, 100, 100, 100, 300];

VC = [2, 1.9, 2.1];

VCH = [0.8, 0.75, 0.8];

AS = [520, 850, 750, 0, 0, 1500, 500, 0];

CS = [500, 200, 400, 0, 700, 500];

Cp = [450, 850,0];

RM = [0, 120, 120, 0, 0, 0,0, 0, 0, 160, 160, 200, 0, 84, 84, 60, 45, 0,70, 70,
70, 0, 0, 0,  0, 0, 0, 80, 60, 0,49, 49, 49, 120, 120, 120];

CV = [1, 0.95, 9, 9.6, 0.15, 0.12];



CPP = [0.8, 0.7, 0.6, 0.6, 0.8, 0.5, 0.6, 0.5, 0.7, 0.6, 0.7, 0.5];

TC = [90 100 210];

PB =[1, 0.5,0.3,0.2, 0.5,0.3,0.2, 0.3, 0.5,0.2, 0.3,0.2,0.5];

IR1 = [1.029, 0.97, 1.029, 1.029, 0.97,0.97, 1.029,1.029,1.01, 1.03, 1.01, 1.01,
1.03,1.03, 1.01,1.01,1.01, 1.03, 1.01, 1.01, 1.03,1.03, 1.01,1.01,1.01, 1.03,
1.01, 1.01, 1.03,1.03, 1.01,1.01,1.01, 1.01, 1.01, 1.01, 1.01,1.01, 1.01,1.01,
1.01, 1.01, 1.01, 1.01, 1.01,1.01, 1.01,1.01,1.01, 1.01, 1.01, 1.01, 1.01,1.01,
1.01,1.01,1.01, 1.01, 1.01, 1.01, 1.01,1.01, 1.01,1.01,1.01, 1.01, 1.01, 1.01,
1.01,1.01, 1.01,1.01,1.01, 1.01, 1.01, 1.01, 1.01,1.01, 1.01,1.01,1.01, 1.01,
1.01, 1.01, 1.01,1.01, 1.01,1.01,1.01, 1.01, 1.01, 1.01, 1.01,1.01, 1.01,1.01,
1.01, 1.01, 1.01, 1.01, 1.01,1.01, 1.01,1.01];



IR2 = [1.4, 0.8, 1.4, 1.4, 0.8,0.8, 1.4,1.4, 1.4, 0.8, 1.4, 1.4, 0.8,0.8,
1.4,1.4, 1.4, 0.8, 1.4, 1.4, 0.8,0.8, 1.4,1.4, 1.4, 0.8, 1.4, 1.4, 0.8,0.8,
1.4,1.4, 1.4, 0.8, 1.4, 1.4, 0.8,0.8, 1.4,1.4, 1.4, 0.8, 1.4, 1.4, 0.8,0.8,
1.4,1.4, 1.4, 0.8, 1.4, 1.4, 0.8,0.8, 1.4,1.4, 1.4, 0.8, 1.4, 1.4, 0.8,0.8,
1.4,1.4, 1.4, 0.8, 1.4, 1.4, 0.8,0.8, 1.4,1.4, 1.4, 0.8, 1.4, 1.4, 0.8,0.8,
1.4,1.4, 1.4, 0.8, 1.4, 1.4, 0.8,0.8, 1.4,1.4, 1.4, 0.8, 1.4, 1.4, 0.8,0.8,
1.4,1.4, 1.4, 0.8, 1.4, 1.4, 0.8,0.8, 1.4,1.4];



IR3 = [0.8, 1.4, 0.8, 0.8, 1.4,1.4, 0.8,0.8,0.8, 1.4, 0.8, 0.8, 1.4,1.4,
0.8,0.8,0.8, 1.4, 0.8, 0.8, 1.4,1.4, 0.8,0.8,0.8, 1.4, 0.8, 0.8, 1.4,1.4,
0.8,0.8,0.8, 1.4, 0.8, 0.8, 1.4,1.4, 0.8,0.8,0.8, 1.4, 0.8, 0.8, 1.4,1.4,
0.8,0.8,0.8, 1.4, 0.8, 0.8, 1.4,1.4, 0.8,0.8,0.8, 1.4, 0.8, 0.8, 1.4,1.4,
0.8,0.8,0.8, 1.4, 0.8, 0.8, 1.4,1.4, 0.8,0.8,0.8, 1.4, 0.8, 0.8, 1.4,1.4,
0.8,0.8,0.8, 1.4, 0.8, 0.8, 1.4,1.4, 0.8,0.8,0.8, 1.4, 0.8, 0.8, 1.4,1.4,
0.8,0.8,0.8, 1.4, 0.8, 0.8, 1.4,1.4, 0.8,0.8];



PlantCapacityIncrease = {1,2,3};

WarehouseCapacityIncrease = {1,2,3};

PlantCIncrease = [100,200,300];

WarehouseCIncrease  = [100,200,250];

Vulnerability = [5,4.8,4.5,4.5,5,4.8,4.5,4.5,1,1.1,2,2];
```

```
BrentCost1 = [1.15, 1, 1.15, 1.15, 1,1, 1.15,1.15,1.15, 1, 1.15, 1.15, 1,1,
1.15,1.15,1.15, 1, 1.15, 1.15, 1,1, 1.15,1.15,1.15, 1, 1.15, 1.15, 1,1,
1.15,1.15,1.15, 1, 1.15, 1.15, 1,1, 1.15,1.15,1.15, 1, 1.15, 1.15, 1,1,
1.15,1.15,1.15, 1, 1.15, 1.15, 1,1, 1.15,1.15,1.15, 1, 1.15, 1.15, 1,1,
1.15,1.15,1.15, 1, 1.15, 1.15, 1,1, 1.15,1.15,1.15, 1, 1.15, 1.15, 1,1,
1.15,1.15,1.15, 1, 1.15, 1.15, 1,1, 1.15,1.15,1.15, 1, 1.15, 1.15, 1,1,
1.15,1.15,1.15, 1, 1.15, 1.15, 1,1, 1.15,1.15];


BrentCost2 = [0.9, 0.9,0.9, 0.9, 0.9,0.9, 0.9,0.9,0.9, 0.9,0.9, 0.9, 0.9,0.9,
0.9,0.9,0.9, 0.9,0.9, 0.9, 0.9,0.9, 0.9,0.9,0.9, 0.9,0.9, 0.9, 0.9,0.9, 0.9,0.9,
0.9, 0.9,0.9, 0.9, 0.9,0.9, 0.9,0.9,0.9, 0.9,0.9, 0.9, 0.9,0.9, 0.9,0.9, 0.9,
0.9,0.9, 0.9, 0.9,0.9, 0.9,0.9,0.9, 0.9,0.9, 0.9, 0.9,0.9, 0.9,0.9,0.9, 0.9,0.9,
0.9, 0.9,0.9, 0.9,0.9,0.9, 0.9,0.9, 0.9, 0.9,0.9, 0.9,0.9,0.9, 0.9,0.9, 0.9,
0.9,0.9, 0.9,0.9,0.9, 0.9,0.9, 0.9, 0.9,0.9, 0.9,0.9,0.9, 0.9,0.9, 0.9, 0.9,0.9,
0.9,0.9,];


BrentCost3 = [1, 1.15, 1, 1, 1.15,1.15, 1,1,1, 1.15, 1, 1, 1.15,1.15, 1,1,1,
1.15, 1, 1, 1.15,1.15, 1,1,  1, 1.15, 1, 1, 1.15,1.15, 1,1,1, 1.15, 1, 1,
1.15,1.15, 1,1,1, 1.15, 1, 1, 1.15,1.15, 1,1,1, 1.15, 1, 1, 1.15,1.15, 1,1,1,
1.15, 1, 1, 1.15,1.15, 1,1,1, 1.15, 1, 1, 1.15,1.15, 1,1, 1, 1.15, 1, 1,
1.15,1.15, 1,1,1, 1.15, 1, 1, 1.15,1.15, 1,1,1, 1.15, 1, 1, 1.15,1.15, 1,1,1,
1.15, 1, 1, 1.15,1.15, 1,1];


fcl = [2000,2500,3000,3000,3000,3200,1800,2200,3100];

fcw = [200, 250, 300, 200, 250, 290, 180, 250, 270];

icl = [3000 6000 6500];

icw = [50 50 50 50 50 50];

iccl=[2500 4500 6800 2500 4500 6800 2500 4500 6800];

iccw=[200 350 400 200 350 400 200 350 400];
```